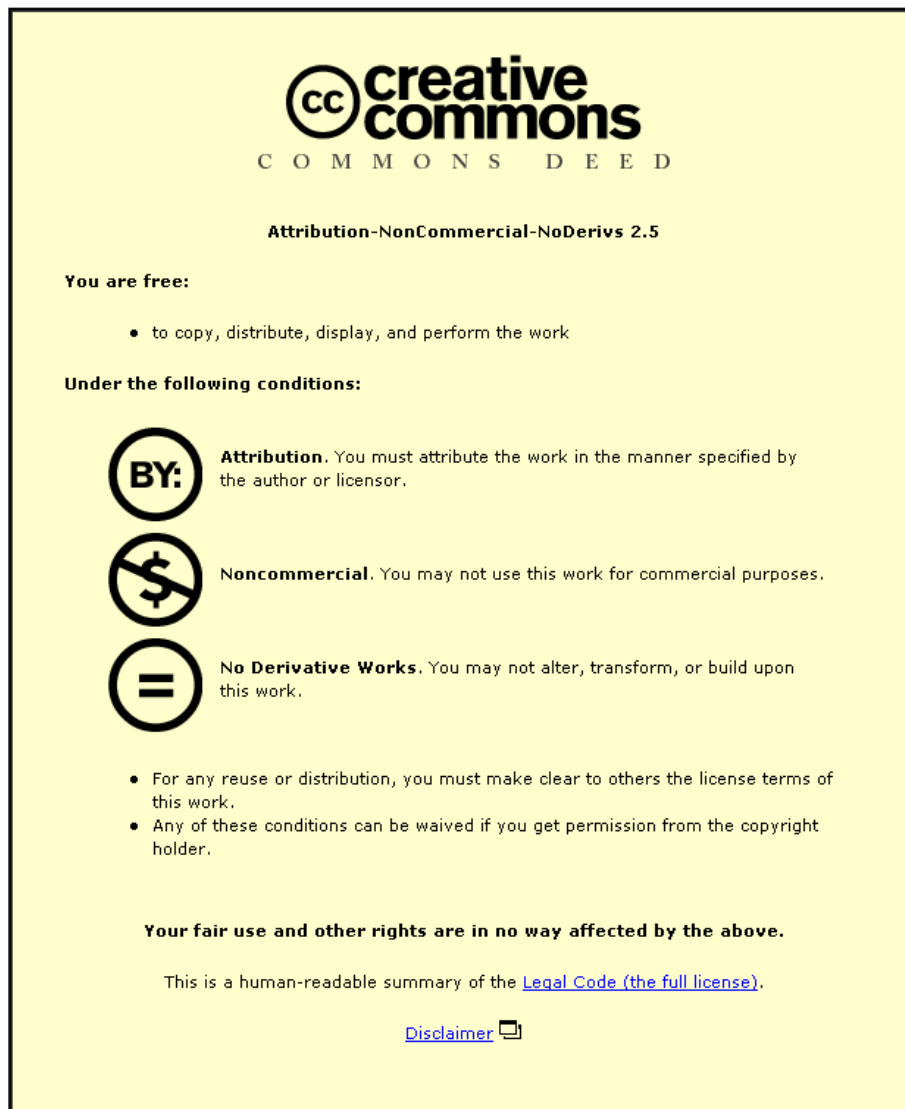
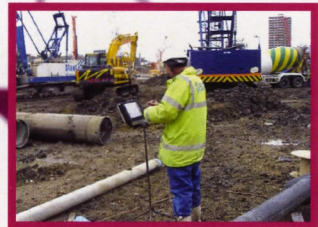
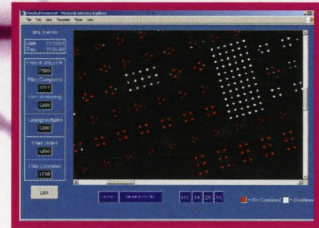


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The Capture and Integration of Construction Site Data

Michael J. Ward



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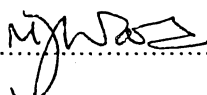
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Certificate of Originality

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Author's signature**Date**

13/09/04

THE CAPTURE AND INTEGRATION OF CONSTRUCTION SITE DATA

By
Michael James Ward

A dissertation thesis submitted in partial fulfilment of the requirements for the award of
the degree Doctor of Engineering (EngD), at Loughborough University

September 2004

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ABSTRACT

The use of mobile computing on the construction site has been a well-researched area since the early 1990's, however, there still remains a lack of computing on the construction site. Where computers are utilised on the site this tends to be by *knowledge workers* utilising a laptop or PC in the site office with electronic data collection being the exception rather than the norm.

The problems associated with paper-based documentation on the construction site have long been recognised (Baldwin, et al, 1994; McCullough, 1993) yet there still seems to be reluctance to replace this with electronic alternatives. Many reasons exist for this such as; low profit margins, perceived high cost; perceived lack of available hardware and perceived inability of the workforce. However, the benefits that can be gained from the successful implementation of IT on the construction site and the ability to re-use construction site data to improve company performance, whilst difficult to cost, are clearly visible.

This thesis represents the development and implementation of a data capture system for the management of the construction of rotary bored piles (SHERPA). Operated by the site workforce, SHERPA comprises a wireless network, site-based server and web-based data capture using tablet computers. This research intends to show that mobile computing technologies can be implemented on the construction site and substantial benefits can be gained for the company from the re-use and integration of the captured site data.

KEY WORDS

Construction site, Data Capture, Mobile Computing, Wireless, Workforce, Integration.

PREFACE

This thesis represents the research conducted between 2000 and 2004 under the Engineering Doctorate scheme at the Centre for Innovative Construction Engineering Loughborough University, UK. The research was undertaken within an industrial context and sponsored by Stent Foundations Limited, a major UK piling and ground improvement contractor.

The essence of the Engineering Doctorate is the solution of one or more significant and challenging engineering problems with an industrial context that can be shown to be of benefit not only to the sponsoring company but also to the wider construction industry and as such, requires that results of the research are published during the project. The structure of the thesis is thus representative of the requirements of the Engineering Doctorate and is divided into two distinct but related parts. The main body of the thesis allows the reader to gain an overview of the work undertaken, while more specific aspects of the research can be found in the papers presented in the appendices at the back of the thesis. Where appropriate, references to the papers are provided throughout the main body of the thesis.

USED ACRONYMS / ABBREVIATIONS

ADSL	Asymmetric Digital Subscriber Line
AGS	Association of Geotechnical and Geo-environmental Specialists
Ah	Amp hour
Auto-ID	Auto-Identification
CFA	Continuous Flight Auger
COSMOS	Construction Site Mobile Operations Support
DECT	Digital Enhanced Cordless Technology
GIS	Geographical Information Systems
GPRS	General Packet Radio Service
GSM	Global Systems for Mobile Communications
HTML	Hypertext Mark-up Language
IEEE	Institute of Electrical and Electronic Engineers
IR	Infrared
IS	Information Systems
IT	Information Technology
MICC	Mobile Integrated Communications for Construction
MSTSC	Microsoft Terminal Services Client
NiCad	Nickel Cadmium
PDA	Personal Digital Assistant
PDF	Portable Document Format
PHP	Hypertext Pre-Processor
RBP	Rotary Bored Piling
SFL	Stent Foundations Limited
SIRIS	Stent Integrated Rig Instrumentation System
SHERPA	Stent Handheld Electronic Piling Assistant
SLA	Sealed Lead Acid
SSID	Server Set Identifier
SQL	Standard Query Language
WEP	Wired Equivalent Privacy
WLAN	Wireless Local Area Network
WNC	Wireless Network Cell
WPMS	Web-based Project Management System

TABLE OF CONTENTS

Acknowledgements	iii
Abstract.....	v
Key Words	v
Preface.....	vii
Used Acronyms / Abbreviations	ix
Table of Contents	xi
List of Figures.....	xiii
List of Tables	xv
List of Papers.....	xvii
1 BACKGROUND TO THE RESEARCH	1
1.1 Problem Definition	1
1.2 General Subject Domain.....	1
1.2.1 Auto-Identification.....	2
1.2.2 Mobile Computing.....	2
1.2.3 Multi-media	3
1.2.4 Automated Data Capture	3
1.2.5 Data Communication and Re-use	3
1.3 Context of Research	4
1.4 Structure of the Thesis.....	4
2 OVERALL AIMS AND OBJECTIVES.....	5
2.1 Project Aims	5
2.2 Project Objectives.....	5
3 RESEARCH METHODOLOGY	7
3.1 Classification of Research Methods	7
3.2 Research Methods in Construction.....	7
3.3 Research Methods in Information Systems	7
3.4 Action Research.....	8
3.4.1 Action Research and User Participation	9
3.5 Research Design	9
3.6 Research Validation.....	10
4 THE RESEARCH WORK UNDERTAKEN	13
4.1 Work Phases	13
4.2 Technology Drift	14
4.3 RESEARCH CYCLE A – EXPLORATION	14
4.3.1 Literature Review	15
4.3.2 RBP Site Process Analysis	15
4.3.3 Development and testing of trial solution.....	19
4.3.4 Observations and Reflections	20
4.4 RESEARCH CYCLE B – DEVELOPMENT	21
4.4.1 Investigation.....	21
4.4.2 Systems Engineering.....	22

4.4.3	Implementation.....	28
4.4.4	Integration	31
4.4.5	Observations and Reflections.....	32
4.5	RESEARCH CYCLE C - ENHANCEMENT	33
4.5.1	Investigation	33
4.5.2	Systems Engineering	34
4.5.3	Implementation.....	40
4.5.4	Integration	41
5	FINDINGS AND IMPLICATIONS	45
5.1	The Key Findings of the Research.....	45
5.1.1	Technologies for use on the Construction Site.....	45
5.1.2	Site Implementation	47
5.1.3	Process Improvements.....	48
5.2	The Contribution to Existing Practice.....	48
5.3	The Impact on the Sponsor	49
5.4	The Implications for Wider Industry	50
5.5	Recommendations for Further Research.....	51
5.6	Critical Evaluation of the Research	51
6	REFERENCES.....	53

LIST OF APPENDICES

Appendices A to E contain full text versions of papers 1 to 5 respectively as referenced in the List of Papers.

Appendix – A: Paper 1	57
Appendix – B: Paper 2	79
Appendix – C: Paper 3	99
Appendix – D: Paper 4	113
Appendix – E: Paper 5	135

LIST OF FIGURES

Figure 1: Action Research ‘Cycle of Spirals’ as defined by Lewin.	8
Figure 2. User Involvement in Action Research Process	9
Figure 3. RDP a site information flow diagram.....	16
Figure 4. RBP construction and levels.....	17
Figure 5: Psion workabout and docking cradle	19
Figure 6. SHERPA system configuration	23
Figure 7. Cellular configuration of the WNC	24
Figure 8. Model I design with solar panel and located on the foreman’s hut.....	25
Figure 9. Model II WNC prototype design and installation on a piling rig.....	25
Figure 10. Tabbed user interface with built-in data verification.	26
Figure 11. Visualisation of concrete entry with page locking.	27
Figure 12. Windows CE touch-screen tablet computer in operation.....	28
Figure 13. Model II WNC prototype located on tower-crane.....	29
Figure 14. Simplified rig interface developed for the Wembley contract	30
Figure 15 Simplified concrete gang interface with ticket pop-up	31
Figure 16. Electronic pile log and soil profile log to BS 5930	32
Figure 17. Architecture of the web-based SHERPA system	35
Figure 18. Web-based data capture interface.....	36
Figure 19. Tablet computer with additional battery pack.....	37
Figure 20. Web-page for the creation of data capture profiles	38
Figure 21. Histogram visualisation of imported pile schedule data	38
Figure 22. Visualisation of site progress through ‘site-viewer’ tool	39
Figure 23: Operation of tablet computer mounted on lectern.....	41
Figure 24: Prime cost analysis graph for contract period	43

LIST OF TABLES

Table 1. Categorisation of Research into Data Capture on the Construction Site.....	2
Table 2. Classification of Research Methods	7
Table 3. Work location and user involvement between stages.....	10
Table 4. Relationship between work phases, research cycles and paper content	13
Table 5. Mapping information processes with data capture technologies.....	18
Table 6. Research project related articles published in trade press	50

LIST OF PAPERS

The following is a list of papers included at the back of this thesis, together with a list of additional published papers that are not included.

Paper 1

Ward, M.J., Thorpe, A., Price, A.D.F. and Wren, C. (2003). SHERPA: Mobile wireless data capture for piling works, *Journal of Computer Aided Civil and Infrastructure Engineering* **18**(4), pp 200-220.

Paper 2

Ward, M.J., Thorpe, A., Price, A.D.F. and Wren, C. (2004). Implementation and Control of Wireless Data Capture on Construction Sites, ITcon Vol. 9, Special Issue, Mobile Computing in Construction, pp. 297-311, <http://www.itcon.org/2004/21>

Paper 3

Ward M.J., Thorpe A, Price A.D.F and Wren C. (2004). IEEE 802.11b Wireless networks: An Enabler for Real-time Data Capture in Construction. *Proc. CIB World Building Congress 2004, Toronto, Canada, 1-7 May, Paper No. 586, p.233 (11 pages)*

Paper 4

Ward, M.J., Thorpe, A., Price, A.D.F. and Wren, C. (2004). Delivering Web-based Project Management Support to Construction Site Workers. *(Submitted to Automation in Construction, June 2004)*

Paper 5

Ward M.J., Thorpe A, Price A.D.F. and Wren C. (2004). The Re-use of site data to Inform Business Processes. *Proc, 10th International Conference on Computing in Civil and Building Engineering, Weimar, Germany, 02-04 June, Paper No. 26, p.76.*

Additional Papers (Not Included in Thesis)

Ward M.J., Thorpe A, Price A.D.F. and Wren C. (2002). Applications of Mobile Computing for Piling Operations. *Proc. 9th Int Conf on Concurrent Engineering, Cranfield University, UK, 27-31 July, pp. 663-67*

1 BACKGROUND TO THE RESEARCH

1.1 PROBLEM DEFINITION

A key factor in the success of any construction company is the successful delivery of individual projects. Assuming that the estimating process is accurate, it is the performance of site activities and project management that dictate if the project is profitable or not. The need for efficient and effective site-based data collection is therefore generic to all construction projects as it forms the backbone of project financial and management control.

Many construction companies currently rely on paper-based systems to manage projects at site level, which may be due to one or a number of factors including:

- perceived cost of IT;
- lack of on-site security;
- short-term contracts resulting in reluctance to implement IT;
- IT literacy of construction workforce;
- maintenance of IT; and
- suitability of IT to withstand the rigours of site.

In order for any benefit to be gained from paper-based site data, they have to be re-entered into electronic format. Such re-keying is generally performed for costing and valuation purposes, with very little use of data being made by engineers or other core business activities, due to the time required converting data into electronic format. However, there are many benefits that can be achieved by electronic site data collection that facilitates the re-use of data, such as:

- time savings from eliminating re-typing;
- improved data integrity;
- data analysis to improve core business activities such as estimating;
- improved knowledge of site processes;
- improved real-time project control; and
- improved company integration and more cohesive processes.

1.2 GENERAL SUBJECT DOMAIN

The application of computing on the construction site has been well researched since the late 1980's and can be sub-divided into four core areas as presented in Table 2. Such research has identified key areas affecting IT implementation, with consideration being given to hardware, software and personnel issues. However, the early applications of construction IT tended to be stand-alone and in many cases required bespoke software and hardware development. The transfer of data was often via hardwired means, limiting the opportunities for real-time data analysis and exchange. More recently, this trend has changed, with many construction related software applications being developed, together with suitable mobile hardware. Furthermore, the advent of mobile communication technologies allows for the timely transfer of data from the site, allowing for integration with real-time data-centric applications.

1.2.1 AUTO-IDENTIFICATION

The two main areas of auto-identification technologies research have been bar-coding and radio frequency identification, from which two main applications have emerged; materials handling and asset management and tracking.

The use of auto-identification technologies within the UK construction industry is low (Muya, et al.1999). Whilst the potential for the use of this technology for communicating delivery data is high, it depends on greater industry awareness and its adoption by all parties involved in construction (Marsh & Finch, 1998). However, further implementation of this technology for materials handling may be slowed-down by the current focus towards e-commerce within the construction industry.

Table 1: Categorisation of Research into Data Capture on the Construction Site

Categories	Methods	Source
Auto -Identification	Barcodes Radio frequency Touch memory	Bell & McCullough (1988) Baldwin, et al. (1994) Bernhold (1990) Jaselskis, et al. (1995) Jaselskis, et al. (2000) Escheverry (1996) Marsh & Finch (1997) Cheng & Chen (2002)
Mobile computing	Notebooks Laptops Tablet computers PDA's	McCullough (1993) Songer & Rojas (1996) Elzarka, et al. (1997) Fayek, et al (1998) Navarette (1999) Phair (2000) Cox, et al. (2002)
Multi-media	Wearable computing Integrated devices Ubiquitous computing Voice activation	Thorpe, et al. (1995) Liu (1995,1997) Alexander (1996, 1997) Vogt (2002) Garrett and Sunkpho (2000)
Automated data collection	Vehicle mounted Sensor systems 3D laser scanners	Kanaan & Vorster (1998) Scott (1999) Liu et al, (2004)

1.2.2 MOBILE COMPUTING

Research into the use of mobile computers in construction has tended to follow developments in technology from early notebook type computers (McCullough, 1993) to PDA's (Cox, et al. 2002). Whilst such research has been primarily technical in nature, a number of core issues regarding hardware and software have been addressed:

- whether existing forms should be mimicked;
- the availability and suitability of rugged hardware;
- size of mobile computing devices and screens;

- ability to read the screen in sunlight; and
- the operability of touch-screens.

1.2.3 MULTI-MEDIA

The emergence of multi-media technologies in the mid 1990's allowed devices to be connected that could be used simultaneously to augment traditional text based data capture with sounds, voice activation and images resulting in two distinct approaches. Wearable systems (Liu, 1995, 1997; Thorpe, et al, 1995) utilising the individual to carry off-the-shelf components and their connections. This type of system was devised because of the impracticality of using devices simultaneously and the unwieldy nature of their connections, making them unsafe to use on site or whilst working. The integrated unit approach provides all of the functionality of multi-media but in a single hand-held unit (Alexander 1996,1997). This approach can now be seen emerging in mainstream technologies such as mobile phones and PDA's with integrated cameras.

1.2.4 AUTOMATED DATA CAPTURE

This technology allows for data capture by the use of on-board computers built-in sensors or devices such as 3D laser scanners. The application of on-board computing technology has been reported in earthmoving by Kanaan and Vorster (1998) and in Continuous Flight Auger (CFA) piling by Scott (1999). Both systems report the benefits of automated data collection as being:

- ease of collection;
- little or no manual input required;
- statistically reliable data; and
- ease of data sharing with other systems.

1.2.5 DATA COMMUNICATION AND RE-USE

Two research approaches have been used to investigate the communication of site data: access and store all data off-site (Baxevanaki, et al. 2001); and access and maintain an on-site data store. (de la Garza, et al. 1998; MICC, 1998). Whilst storing all data off-site may be desirable for security and accessibility it relies heavily on both local and global communications protocols. There are many technologies available to help achieve this, however, such an approach raises many issues, for example:

- availability of communication technology;
- signal coverage to the site;
- reliability and cost of connections; and
- communication between technologies.

The use of an on-site data store enables greater control and access to the data for site personnel, without concern for communication protocols. This also allows tailoring of data transfer between the site and head office, depending on the availability of technologies. However, this may be at detriment to security and accessibility to the data for off-site personnel.

1.3 CONTEXT OF RESEARCH

The philosophy of the Engineering Doctorate is to undertake practical research in an industrial environment with research performed in conjunction with a sponsoring company. The sponsoring company for this project is Stent Foundations Limited (SFL), a major ground engineering contractor specialising in piling works. The company is a subsidiary of Balfour Beatty Plc and primarily operates as a specialist sub-contractor on small, short-term projects (typically 4-6 weeks) and multi-million pound projects (Channel Tunnel Rail Link, Wembley Stadium). Three main piling techniques are carried out by the company, Driven, Continuous Flight Auger (CFA) and Rotary Bored Piling (RBP).

Over recent years, SFL have been investigating the building blocks to capturing and transmitting information that it requires and generates on site, using electronic methods. Much of this previous work has been centred on automated data collection techniques using the Stent Integrated Rig Instrumentation System (SIRIS) utilising ‘on-board’ computers on the piling rigs within the CFA process. There is however, a large amount of information that cannot be captured in this way and is currently captured using paper-based data collection systems, which do not lend themselves to efficient re-use of data. Although historical project records exist, these are in an unwieldy paper format and any extraction of information requires extensive man-power which can be a limited resource in today’s business environment. This redundancy of data has led to the creation of a ‘museum of information’ that may only be visited infrequently, leading to a large amount of valuable data effectively being lost to the company.

Capturing data electronically will remove this redundancy thus allowing the re-use and manipulation of the data throughout the company. Once the data are captured, there is the major knowledge management problem of distributing the data to the right repositories and manipulating it to provide information to guide the future decisions of the company in winning work and efficiently executing new work

1.4 STRUCTURE OF THE THESIS

The Engineering Doctorate requires the publication of work throughout the life of the project in refereed journals and conferences and this is reflected in the structure of the thesis. Published work is presented at the back of the thesis in the form of papers and should be read in conjunction with the remainder of the thesis.

2 OVERALL AIMS AND OBJECTIVES

All project work was performed in the context of rotary bored piling technique, an initial project brief provided by SFL was developed resulting in the following aims and objectives.

2.1 PROJECT AIMS

- Assess data collection methods used and how these integrate with site construction processes.
- Investigate the state-of-the-art in available technologies for site data capture.
- Replace existing paper-based documentation with electronic alternatives.
- Provide the data in a suitable format for re-use throughout the business.
- Provide tools for accessing collected data both on and off-site.
- Provide access to information to the client in electronic format.

2.2 PROJECT OBJECTIVES

- Understand the requirements for site data collection systems within piling.
- Understand the communication and data requirements of the site.
- Improve the quality of data gathered on the construction site.
- Understand the obstacles to implementing workforce driven data capture on the construction site.

3 RESEARCH METHODOLOGY

3.1 CLASSIFICATION OF RESEARCH METHODS

One of the most common classifications of research is between qualitative and quantitative methods (Table 2). Quantitative research methods were originally developed in the natural sciences to study natural phenomena, whilst qualitative research methods were developed in the social sciences to enable researchers to study cultural and social phenomena.

The distinction between the two can also be related to the degree of thinking participants. Natural science research consists of events and facts that are unrelated to what anybody thinks or says about them, whereas events studied by social sciences have thinking participants, which have a direct bearing on the likely outcome of the research.

Although most research is conducted using either qualitative or quantitative methods, there exists a third type, triangulation, which combines one or more research methods in one study

Table 2: Classification of Research Methods

Research Classification		
Type	Quantitative	Qualitative
Methods	Surveys Laboratory Experiments Formal Methods Numerical Methods (mathematical modelling)	Action Research Case Studies Participant Observation Interviews
Area	Natural Sciences	Social Sciences

3.2 RESEARCH METHODS IN CONSTRUCTION

The broad spectrum of construction research utilises both qualitative and quantitative methods depending on the type of research. Traditionally scientific based quantitative methods have been adopted particularly for analytical based research such as structural or materials behaviour and where there is no involvement of a thinking participant. However, the level of human participation and consequently thinking participants within construction, requires the use of more qualitative research methods, this is particularly pertinent to the area of construction management where case studies and action research techniques have been largely employed.

3.3 RESEARCH METHODS IN INFORMATION SYSTEMS

There have been many debates within the Information Systems (IS) community regarding research methodologies (Mingers and Stowell, 1997; McFarlan, 1984; Mumford, et al 1985), however, the underlying classification between quantitative or

qualitative approaches still remains. The advent of IS research concentrated on technical aspects of IS and consequently resulted in the early adoption of quantitative research methodologies, however, latterly there has been a recognised shift towards more qualitative approaches (Alavi and Carlson, 1992). Some researchers argue that this was caused by difficulties in getting IS to work effectively within organisations (Backhouse et al. 1991). However, the increased use of IS throughout the business world has had a significant impact on the field of IS research, requiring researchers to have an understanding of both technological and behavioural factors (Avison and Fitzgerald, 1991).

3.4 ACTION RESEARCH

Action Research is a qualitative method originating in the area of social sciences and educational research and one that is closely related to organisational behaviour and change management and has been used in both construction management and IS research. It is an applied methodology combining ‘Action’ and ‘Research’ research to decide actions, undertake actions and research results of actions to promote or guide further action. The original formulation of which is based on a spiral of cycles of planning, acting, observing and reflecting, Lewin (1946), Figure 1.

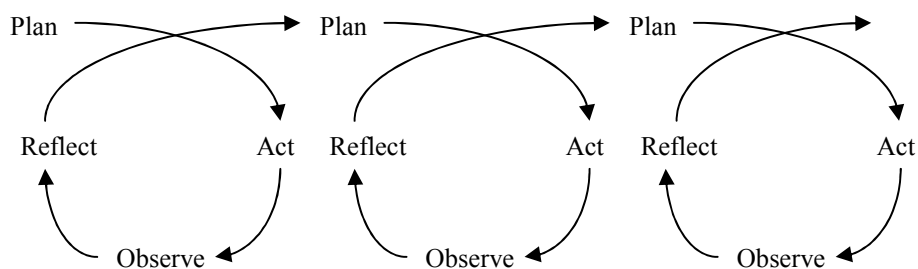


Figure 1: Action Research ‘Cycle of Spirals’ as defined by Lewin.

Planning is seen as starting with a general idea and a certain objective, followed by more fact-finding about the situation, from this an overall plan is developed together with a decision of the first step to take. This is then followed by a series of actions, observations and a period of reflection with results and outcomes from the first cycle used to guide actions for the next cycle, and so on. This cycle was simplified by Stringer (1997) who suggested the existence of three stages, look, think and act, again based on the premise that the original question is not fully defined.

The action research approach suits the requirements of this project well, as the original question from the sponsoring company was generalised to the area of site data collection, thus requiring a period of investigation and grounding in the subject. The project aims and objectives, for data collection and re-use, also suggest that a cyclic development and implementation strategy be adopted. Action research also sits well with the philosophy of the Engineering Doctorate scheme, which is to undertake practical research within an industrial environment, this is further enforced with the following quotations related to action research.

'Action research aims to contribute both to the practical concerns of people in an immediate problematic situation and to the goals of social science by joint collaboration within a mutually acceptable ethical framework' (Rapoport, 1970).

'To make academic research relevant, researchers should try out their theories with practitioners in real situations and real organisations' (Avison, et.al. 1999).

3.4.1 ACTION RESEARCH AND USER PARTICIPATION

By its very nature, action research requires some user involvement in the research process itself. This was investigated by Whyte (1989) who distinguished three forms, depending on degree of user participation in the research process. The first being a clinical, problem-orientated approach, undertaking tasks, and reporting results with minimal user involvement in the research. The second type being an attempt to make a change within an organisation with restricted user participation, usually to making decisions about solutions proposed and developed by the researcher. The third, 'participatory action research' involves all users in all stages of the research project.

By accepting the involvement of users within action research, Karlsen (1991) raises prospecting researchers awareness of potential problems associated with user participation, suggesting that full participatory research can risk the watering down of ideas to provide compromises for all parties through the process of discussion, with discussion itself promoting conservatism.

3.5 RESEARCH DESIGN

The nature of this project is such that it does not aspire to full participatory action research, but does have the effect of making changes to the organisation and decisions to be made on any implementations or developments. This in effect produces a driving force from within the company as to how the project should develop and what it should contain. Whilst the importance of users is recognised and is closely related to the nature of the Engineering Doctorate, user involvement in the project was limited to the process level, as this is where the majority, if not all, of their knowledge lies. This is depicted in Figure 2, which indicates the user participation level within the research process based on questions posed by the research.

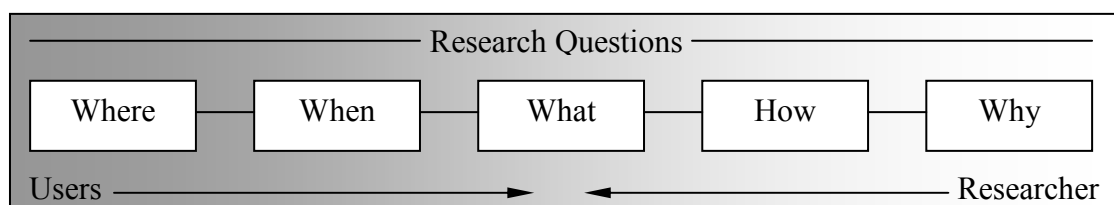


Figure 2: User Involvement in Action Research Process

The cyclic nature of action research dictates that only the planning stage of the first cycle be known at the outset, with the remainder of the cycles developed as the research progresses. The research undertaken completed three main cycles (see Figure 3), with

each cycle having four elements as described by Lewin; planning, acting observing and reflecting. Due to the nature of this research, the level of user involvement and location in which the work was conducted varied between individual stages (Table 3).

1. The planning stage of all cycles was conducted both on and off-site, with user involvement sought where necessary. This involved observations of user behaviour their working practices and consideration of processes carried out on site. This stage was also used for development of systems and technologies for site use.
2. The action phase was essentially site implementation of developments and as such was wholly conducted on-site. User involvement in this stage was limited to training and teaching of how systems worked and were to be used. In all cycles this had the effect of instigating secondary 'mini' cycles to solve particular problems that arose.
3. The observation stage was also conducted on site. User feedback was gained through informal discussions with users about how the system could be improved and from observing user behaviour and use of the implemented systems. Whilst structured interviews and/or questionnaires could have been used, these were deemed inappropriate due to; the limited number of personnel involved and the different perspective of the system between users such as site workers and engineers.
4. Reflection of work was undertaken off-site without any user involvement. This involved the rationalisation of actions and observations to inform the planning phase for the next cycle.

Due to the nature of the work, additional sub-cycles emerged within each of the main identified cycles of research. These took the form of minor changes and additional developments to enhance original development work carried out in each stage.

Table 3: Work location and user involvement between stages

Stage	Location	User Involvement
Planning	Off and On-site	Yes (restricted)
Action	On-site	Yes
Observation	On-site	Yes
Reflection	Off-site	No

3.6 RESEARCH VALIDATION

Unlike traditional scientific approaches to research, action research has been criticised for lacking rigour and standard methods of validation, as the cyclic process can be disorderly and make it difficult to trace a clear connection between outcomes and actions taken. This was discussed by Karlsen (1991), who suggested that validation can be derived from a number of sources within the research.

1. The process contributes to corroboration because the assumptions about the causal relationships on which actions are based will continuously be

tested. The recirculation of data sets and derived hypotheses in effect provide a control that is scientifically satisfactory.

2. The corroboration of users and practitioners in evaluating and interpreting actions opens up the research process to validation through consensus.

The structure of the Engineering Doctorate allows for validation as the research progresses, through the publication of work in refereed journals and conferences. In addition, the research required the development of systems for piling works to be implemented at both a company and individual level. Hence the adoption of the developed solutions by the sponsoring company, but more importantly the field workers, in itself provides a level of validation to the research.

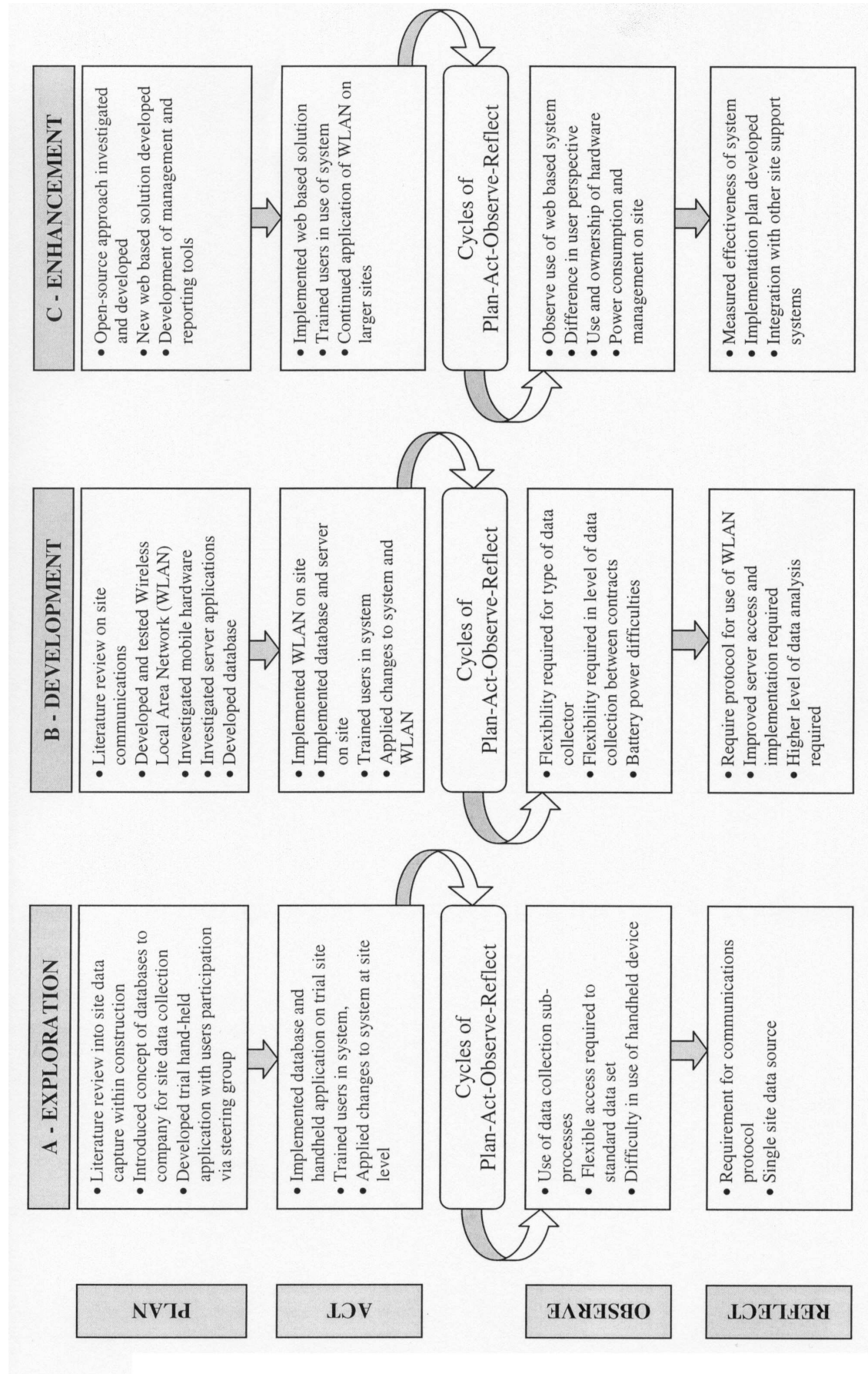


Figure 3: Main research cycles observed in action research approach

4 THE RESEARCH WORK UNDERTAKEN

This section describes the research work undertaken throughout the Engineering Doctorate program. It is intended that this section should provide an overview of the work, the evolution of the research and its relationship to other work carried out in the domain. References have been provided within this section to the papers provided at the back of the thesis. However, it is recommended that these should not be read in full before completing this section.

4.1 WORK PHASES

To further assist in the understanding of the research process and the work undertaken, four work phases have been identified, all of which were conducted by the author. The relationship between work phases, research cycles and paper content has also been established (see Table 4).

Table 4: Relationship between work phases, research cycles and paper content

Research Cycle			Work Phase	Paper Content				
A	B	C		1	2	3	4	5
✓	✓	✓	Investigation	✓				
	✓	✓	Systems Engineering	✓			✓	✓
	✓	✓	Implementation	✓	✓			✓
		✓	Integration			✓	✓	✓

The work undertaken within each phase is described as follows:

- **Investigation** – Describes work undertaken to assist in the understanding of the identified problem such as, literature reviews, analysis of existing site operations and systems, personnel observations, and implementation of trial solutions. Due to the cyclic nature of the research, the majority of work within cycle A (exploration) was conducted in this phase, results from which could be used to inform further research cycles.
- **Systems Engineering** – This phase describes the development of systems for the capture and integration of construction site data and includes, system analysis, programming, software development and hardware construction. Systems Engineering was conducted in both cycles B and C.
- **Implementation** – Describes the implementation of work undertaken in the systems engineering phase and includes factors such as; training, site implementation, system management, user interaction, system operation and performance.
- **Integration** – This phase explores the integration of systems and data within the company at both site and office level. In addition, the potential for integration of the developed systems throughout the construction industry has been addressed.

Due to the nature of the project it was necessary to conduct research work both in the office environment and out on the construction site, office work was undertaken at various SFL offices throughout the country and at Loughborough University. Site work was undertaken at the following construction sites throughout London, which became operational throughout the period of research:

- Albion Wharf, Battersea;
- Kings Cross/St Pancras Underground Station Redevelopment;
- Wembley National Stadium Redevelopment;
- White City Retail development, Shepherd's Bush; and
- Arsenal F.C 'The New Highbury', Islington.

The RBP process was identified by the sponsoring company as a key area of the business prior to commencement of the research and this is where the majority of the work phases were conducted. Due to the existing use of automated data capture techniques within the Continuous Flight Auger (CFA) process, data from these together with those collected in the systems engineering and implementation work phases were used in the integration phase.

4.2 TECHNOLOGY DRIFT

Due to the nature of the research, better mobile computing devices with greater communication capabilities were likely to emerge throughout the period of the research. During the initial phases of research, the number of mobile devices was limited and although PDA's were starting to emerge as a potential way forward for mobile computing, these were still limited in functionality. Local communication of data between mobile computing devices and desktop PC's was still restricted to hardwired means using docking cradles or serial port connections. At best, the emergence of infrared (IR) technology allowed for data to be transferred without the use of wires, however, this was often fraught with difficulties in alignment of IR scanners between devices. Although Global Systems for Mobile Communications (GSM) could potentially be used to transfer data over longer distances, there was a lack of communications hardware that could be integrated with mobile computing technologies and even where this could be achieved, this often required the coupling of a mobile phone with a computing device and often at the expense of restricted bandwidth. Hence, the philosophy for this research was to utilise currently available technologies that could practically be used, thereby eliminating the risk of delaying the research whilst waiting for potentially better mobile computing equipment that may or may not emerge.

4.3 RESEARCH CYCLE A – EXPLORATION

The main emphasis of the first research cycle was to conduct exploratory work to provide grounding in the general subject domain of site data capture and to understand the RBP site processes carried out within SFL with respect to pile construction and data collection. To achieve this, three main areas of work were undertaken:

- a literature review;
- RBP site process analysis; and
- the development and application of a trial solution.

These were followed by a period of reflection and observation in order that further decisions could be made to advance the research project and inform further research cycles.

4.3.1 LITERATURE REVIEW

The intention of the literature review was to explore results of previous work which could be used to assist in the selection of suitable data capture solutions that could be applied to the RBP process. These were broadly categorised as follows:

- Auto-identification techniques;
- Mobile Computing;
- Multi-media; and
- Automated data capture.

Auto-identification techniques have predominantly found favour in the area of materials handling through the utilisation of simple bar-coding techniques (Baldwin, et al, 1994; Chen, et al, 2002) and have more recently been expanded to integrate with GIS systems for progress monitoring applications (Cheng, et al, 2002). The potential for increased data handling, through the use of radio frequency data tags, has also been investigated, with potential applications cited in asset tracking and building maintenance (Jaselskis, et al, 2000; Yabuki, et al, 2002).

Due to their roots in personal computing, many mobile computers are capable of performing a variety of work functions via specific task related software and applications. However, much research in this area has concentrated on the use of mobile computers for inspection and reporting tasks by *knowledge workers* and engineers (Songer and Rojas, 1996; Elzarka and Bell, 1997; Cox, et al, 2000).

A significant amount of work has been carried out on integrating mobile computing functions with the human form, with early work in this field utilising wearable computing devices such as tablet computers, heads-up displays and hardhats with integrated digital cameras (Thorpe, et al, 1995; Liu, et al, 1997). This area of research continues to develop with the desire to further integrate mobile computing into everyday construction activities through 'ubiquitous computing' devices (Vogt, 2002; Elvin, 2003).

Distinct, but related to the previous three examples, automated data capture involves the use of computers and devices to automatically capture data from a variety of sources, utilising technologies such as:

- on-board computers to automatically log data from machinery such as excavators and piling rigs (Kanaan and Vorster, 1998; Scott, 1999);
- embedded sensors for inspection and monitoring the integrity of structures (Akinci, et al, 2002; Gordon, et al, 2004); and
- 3D laser scanners to generate usable models of the construction site for health and safety monitoring and quantity surveying. (Liu, et al, 2004; Changwan, et al, 2004).

4.3.2 RBP SITE PROCESS ANALYSIS

A series of site visits were made to analyse the RBP construction process, from which an understanding of both the construction sequence and existing site communications was gained.

4.3.2.1 RBP construction process

The following five distinct construction phases were identified within the RBP process.

1. The auger is used to pre-bore a hole to allow the insertion of a temporary casing. A temporary steel casing tube is inserted into the ground at the position of the pile to provide support to the surrounding earth and ensure that the pile is bored vertically by providing a guide to the auger.
2. The auger drills through and below the casing, removing the soil and producing an empty bore. Support fluid such as bentonite or polymer may be used at this stage to provide support to unstable soils such as sands and gravel.
3. A pre-fabricated reinforcement cage is placed into the bore (the type and length of the cage must conform the scheduled requirements).
4. Ready-mixed concrete is poured into the pile to the correct level. Details relating to each pour are recorded. (When support fluid is used a tremie pipe is used to ensure that the concrete is placed below the fluid).
5. The temporary casing is removed and the pile head is cut-off to accept a pile cap.

4.3.2.2 RBP data collection process

The existing process relies heavily on paper-based documentation completed before, during and after the creation of the pile, with many actors involved in the data dissemination and capture process. Figure 3 shows a typical site information flow diagram for the creation of rotary bored piles, which was developed after observations and discussions with site managers, foremen and site operatives.

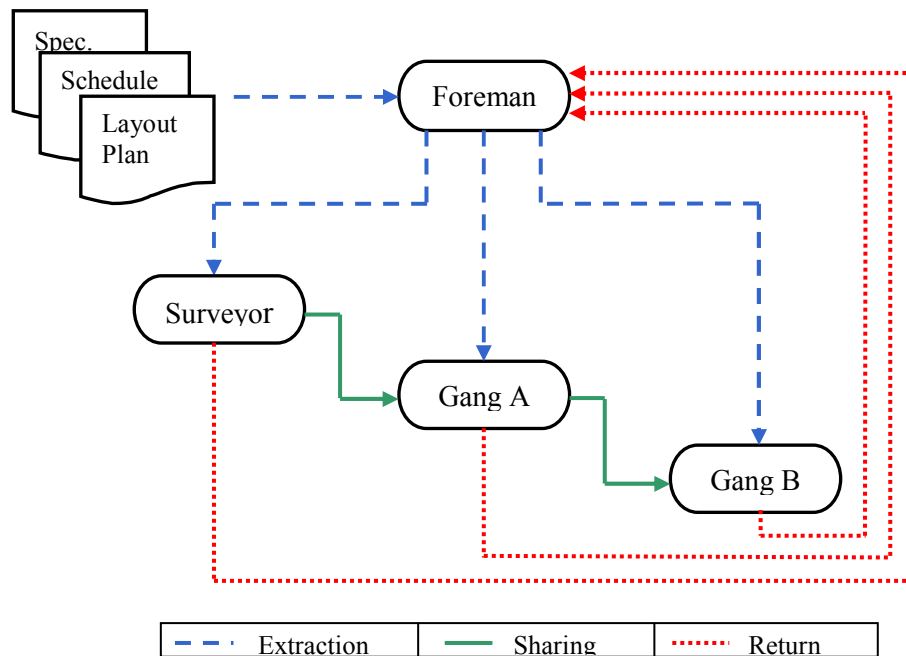


Figure 3: RBP site information flow diagram

Pile design data such as pile co-ordinates, toe level, cage level, concrete level and cut-off level are extracted by the foreman from relevant documents such as the specification, pile schedule and pile layout drawing. These data are then distributed to

workers on the site. During pile construction, data may be collected by a number of personnel as follows:

- **Surveyor** – Pile co-ordinates are used by the surveyor for setting out the pile position on the site. Once the casing has been installed, the top level is taken and used as the datum for all other pile construction measurements such as toe level, cage level, concrete level and cut-off level (see Figure 4).
- **Drilling gang** – Comprising of a rig driver, banksman and chargehand, this gang install the temporary casing, drill the pile and extract the casing on completion. During excavation, the banksman measures the depth of the pile from the top of the casing by tape and may also be required to produce a soil profile log of the bore by recording the type and depth for each strata type excavated. In addition, where support fluid is used, this may be monitored and its status recorded during drilling.
- **Concrete gang** – Depending on the type and size of pile, the number of staff within this gang can vary but typically includes, a concrete ganger, chargehand and a number of general labourers. Their duties include the installation of the reinforcement cage and placement of the concrete.

During construction, all data and measurements are compared against the design schedule and contract tolerances. However, in order to do this, manual calculations such as depth to toe, casing and cut-off levels from the top of the casing are performed at site level and information such as casing level and drilled toe depth has to be shared between site workers, factors that potentially place the integrity of the pile at risk. All data are collated by the foreman who's task is to complete contract documents such as pile logs and concrete records using the data collected on site, which in some cases may be missing or incomplete.

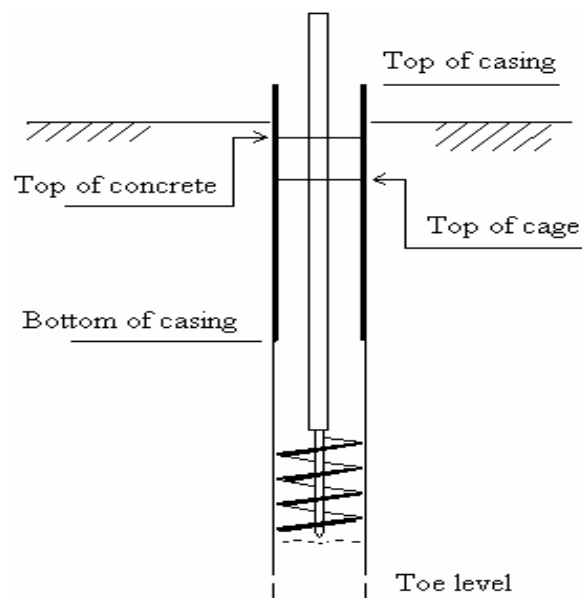


Figure 4: RBP construction and levels

4.3.2.3 Problems with existing data capture methods

As piling is one of the first operations on the site, pile design information is often incomplete or provided late. Piles may be constructed ‘just-in-time’ using up-to-the-minute information provided by the client or designer. Such information may be provided verbally or via paper that must be transferred to the working gangs on the site prior to pile construction, which alone may lead to duplication and multiple revisions of documents being used on the site.

The current methods used for recording the pile information not only duplicate effort but, potentially place the integrity of the pile at risk. Any data transfer errors made from the schedule or miscalculations during pile construction can result in non-conforming piles being constructed leading to additional costs, delays and client dissatisfaction. The construction site is not a suitable environment for paper documentation, a fact that is particularly true in the piling industry where heavy plant and large volumes of excavated soil can result in difficult and muddy site conditions, especially during the winter months. In addition, there is a high risk of incomplete or missing information from the loss of paper-based documents such as materials delivery notes.

Active involvement in the piling works of the personnel responsible for data capture can mean that information gathering and data recording duties are secondary to completing the pile on time and within schedule. Bonus schemes are used to encourage the piling gang to maintain and exceed the program of works; however, it could be argued that they have a potentially detrimental effect on quality of construction and quality of records.

4.3.2.4 Technology mapping

Data capture methods observed from the literature review were mapped against the existing site processes to discover potential matches between technologies and data collection requirements (see Table 5).

Table 5: Mapping information processes with data capture technologies

Working Gang	Information Process	Auto-ID	Mobile	Multi-media	Auto-mated
A	Casing	✓	✓		
A	Drilling		✓		✓
A	Soil Profile		✓	✓	
B	Support Fluid		✓		
B	Reinforcement cage	✓	✓		
B	Concreting	✓	✓		

Auto-ID has proven to be a viable solution for materials and asset management, a factor reflected in Table 5. However, with the exception of placing auto-identification tags on the temporary casing, the practical application of this technology to materials management requires the direct involvement of suppliers.

The flexible nature of computing and ability to write bespoke applications for a variety of platforms and devices suggests that mobile computing could be practically applied to any of the identified information processes.

Multi-media devices could potentially be used to record all of the construction details through the use of voice recognition software and images. However, the relative infancy

of voice recognition software and requirement for voice training, limit the practical application of such technology to the RBP process.

There is limited potential for the use of automated data capture within rotary bored piling, with only information from the pile drilling process potentially available for capture, however, this has been difficult to justify due to the cost of implementation. Whilst the potential for embedding sensors within piles may be an appropriate solution for the future, it would only be practical for piles that are visible above the ground such as in a contiguous wall.

4.3.3 DEVELOPMENT AND TESTING OF TRIAL SOLUTION

In common with previous research into construction site data collection (Songer and Rojas, 1996; Elzarka and Bell, 1997; Cox et al, 2002), a prototype system was developed to trial the electronic capture of RBP piling data by the workforce. This approach allowed for simple applications to be developed and tested with limited initial outlay, the results of which can then be used to inform further decisions and research work. The main drivers behind the development were:

- to test the integration of a mobile computing device with working practices;
- to test the functionality and usability of hardware; and
- to gauge user reaction to system implementation.

The system was tested for a period of eight weeks at Albion Wharf, London and comprised a single Psion 'Workabout' computer with integrated barcode reader (Figure 5) and a stand-alone desktop PC located in the site office with a docking cradle and back-end Microsoft (MS) Access database.

During the testing phase, existing paper-based systems remained in place, enabling observations and comparisons to be made between the trial solution and existing data collection methods.



Figure 5: Psion workabout and docking cradle

An off-the-shelf software tool, 'PowerSurvey' was selected for initial application and testing of data collection on the site. 'PowerSurvey' is a menu-driven text-based data entry system aimed at the building surveying market for the recording of structured task data such as condition inspections and was deemed suitable for the initial testing phase due to the rapid development and deployment that could be achieved.

A bespoke data capture application was designed around the identified RBP phases, allowing users to enter levels and pile dimension data against the scheduled pile data. The system removed the need for manual calculations out on site and provided for minor checks of the data entered on site.

A back-end MS Access database located on the site PC was created to store pile design schedules and to synchronise data with the Psion. Pile schedules from excel spreadsheets were imported into the database from which they were transferred to the Psion via the docking cradle. All data collected on site were stored within the Psion until the end of the day when it was transferred back into the database via the docking cradle. Concrete deliveries were also recorded on site, by scanning the barcode located on the concrete delivery note utilising the integrated barcode scanner within the Psion device.

4.3.4 OBSERVATIONS AND REFLECTIONS

From practical implementation of the trial system, the following observations and reflections were made.

- **Collaborative Information sharing** - There is a culture of collaborative information sharing on the site, whereby data recorded by the banksman (such as casing level or toe level) are used by other workers to position cages and deliver correct concrete volumes to the pile (see Paper 1). Because of the dislocated nature of the working gangs, the use of a single device shared between working gangs did not prove practical. Therefore, multiple devices would be required with the ability to access and share data in real-time between working gangs.
- **Use of a Common Data Store** - Although up to 50 piles could be loaded onto the Psion at the start of the day, unforeseen circumstances such as changes to design schedules, breakdowns and changes in working areas, required that the Psion be returned to the site office for re-loading and synchronisation of missing pile details. This proved impractical for use on the site, increased the potential for detrimental effects on productivity whilst awaiting the most up-to-date data and could potentially place the integrity of work at risk. Site users required the ability to access relevant design data for any pile anywhere on the site at any time, without the need for returning to the site office.
- **Reducing The Burden of Data Management** - Whilst construction workers showed an ability to undertake the simple data capture tasks during their work, they showed resistance to undertaking additional administrative tasks such as the synchronisation and management of data. It is believed that this was due to the fact that unlike *knowledge workers*, the data collection task undertaken by the site workforce is secondary to their day-to-day work, and the captured data would not directly be used by the workforce. As such, whilst they are prepared to record data at site level, site workers see no benefit in undertaking the administration of the system perceiving this to be an engineer's role. This could be resolved by reducing the responsibility of the site users for the transfer of data by utilising a thin-client application.
- **Maintaining Data Integrity** - Due to the potential risk of data loss caused by a damaged or lost device in difficult site conditions, it would be preferable to limit data storage on the computing device. This would have the effect of making the devices operate as thin-client to the site PC, requiring some form of site based communications protocol and a server-based database system.
- **Hardware Functionality** - The size of the Psion keypad was reported by users as impractical for use when wearing gloves whilst the three line text-based

screen proved too small to read. As the majority of user input was level and volume data, a full alphanumeric keypad was deemed unnecessary, and although previous research had cited factors such as ‘small enough to fit in pocket’ (Rebolj et al, 2002) users suggested that a larger touch-screen that could be operated with the finger, would be a more suitable solution.

- **System Potential** - The data collection system was shown on a number of occasions to highlight potential non-conformances that would otherwise have occurred using only the traditional paper-based system, such as piles being constructed too shallow (in some instance up to 1.5m short), incorrect positioning of the steel cages and incorrect concrete casting level.
- **Barcodes on Concrete Delivery Tickets** - Although the barcode on the concrete ticket could be scanned using the Psion device, the resulting code related to a unique key on the concrete suppliers database. This was not sufficient to provide a quality document to the client who require a minimum of concrete ticket number, volume and mix type. Observations and tests on concrete tickets from other SFL concrete suppliers suggested the use of a similar restricted access code type. It is suggested that concrete delivery tickets should be standardised throughout the construction industry to include a barcode with a minimum, ticket number, volume and mix type. However, there are still a very large number of batching plants throughout the UK with their own delivery note system, which may or may not allow the creation of such a barcode and may prove costly to implement for the supplier.

4.4 RESEARCH CYCLE B – DEVELOPMENT

As indicated in Table 4, investigation, systems engineering and implementation work was conducted within cycle B and is described within this section. This is followed with observations and reflections to inform research cycle C.

4.4.1 INVESTIGATION

Results from research cycle A, suggested that local site-based communications would be a key factor to successful sharing and utilisation of data within the RBP process. A study of previous research and currently available technologies identified two potential approaches for the provision of a local data communication network, these being Digital Enhanced Cordless Technology (DECT) and IEEE 802.11b wireless local area networks.

The Mobile Integrated Communications in Construction (MICC) project, (MICC, 1998) supported by the European Commission, investigated the use of an integrated framework to provide voice and data communication to all workers on a construction site. The research was mainly based on Digital Enhanced Cordless Technology (DECT) and proved successful for voice communication but limited for data communication due to the lack of available hardware.

The use of IEEE 802.11b was identified as a viable solution to the problem of real-time data capture on construction sites (de la Garza and Howitt, 1998) with main advantages cited as no service provider charge and higher data transfer rates than other

technologies. However, this research identified the following potential difficulties with the technology:

- the need to reconfigure the network to meet the changing site environment;
- relatively small coverage area;
- the need for ongoing maintenance;
- low data rate 500kbps making it unsuitable for video transmission; and
- lack of security, allowing easy access to the network by computer hackers.

The COSMOS project (Construction Site Mobile Operations Support), proposed a communication infrastructure to link the construction site to the company's head office through the use of Internet technologies (Baxevanaki et al, 2001). The COSMOS project used both DECT and IEEE 802.11b technology to provide mobile data support within the construction site, with a 5.2 GHz HiperLAN backbone for longer distances (up to 1km).

Both the MICC project and de la Garza's work identified the site office as a suitable location for a centrally located site database to which all users stored their data. However, the COSMOS project focussed on accessing a central data store located at the company's head office, which was achieved through the use of a satellite link. Both MICC and COSMOS utilised DECT as the main protocol for establishing voice and data communications on the site. However, DECT has since found greatest application in the cordless telephone market with limited success within data communication. This could be attributed to the increased presence of IEEE 802.11b WLAN equipment, which now has a significant installed base and a superior data transfer rate of 11Mbps compared to the 552 kbps of DECT.

Due to the nature of work, the criticality of data within the RBP process and the availability of data communication protocols that could be practically used between the site and head office, a wholly site-based system was deemed more appropriate, than the operation of a remote system from the head-office. In addition, this would limit the possible number of failure points in communication.

4.4.2 SYSTEMS ENGINEERING

This work phase resulted in the creation of a three-tier system, the **Stent Handheld Electronic Piling Assistant (SHERPA)**, comprising: a site based server; wireless tablet computers; and an adapted IEEE 802.11b wireless local area network (Figure 6). This section aims to briefly describe the development and implementation of the SHERPA system.

4.4.2.1 The creation of a wireless local area network

The IEEE 802.11b protocol was selected for the creation of a wireless local area network (WLAN) on the construction site. Understanding the requirements from research cycle A together with results of previous work, helped to identify a number of key requirements for the development of the WLAN, these being:

- **Portability** - Achieving a portable system that can be easily reconfigured to meet the changing site environment taking consideration of demolition work, creation of superstructure and access to different areas of the site for piling works.

- **Scalability** - The size and duration of construction projects can vary enormously, therefore any networking solution should be able to be easily scaled both up and down to suit the site.
- **Cabling** – Network cabling is not only unsuitable for use on the construction site but would also severely restrict the ability to easily alter the structure of the network to reflect working practices. Whilst the IEEE 802.11b protocol has gained popularity for replacing traditional wired LAN in offices, it is now being applied in other environments with the emergence of outdoor public WLAN and ‘hotspots’ in airport lounges and motorway service stations. However, in all instances, such networks allow limited roaming capability for users (typically up to 50m from an access point) without losing connection. This restriction is a function of the network design, in that a wired backbone is used on which a server resides to provide functionality to the user (see Figure 7). This essentially fixes the wireless network in place and does not allow for flexibility in re-locating the network.
- **Maintenance** - The number and location of sites on which the company work at any one time can vary enormously. Therefore, the need for a low maintenance, easily installed network is essential.
- **Power** – Many construction sites do not have access to mains power and thus rely on generated power. To provide generated power to each access point would require the installation of a power cable or a small generator to each access point. This would be costly, require the use of an electrician and severely restrict the flexibility of the network. A self-contained low-maintenance power solution was therefore required.

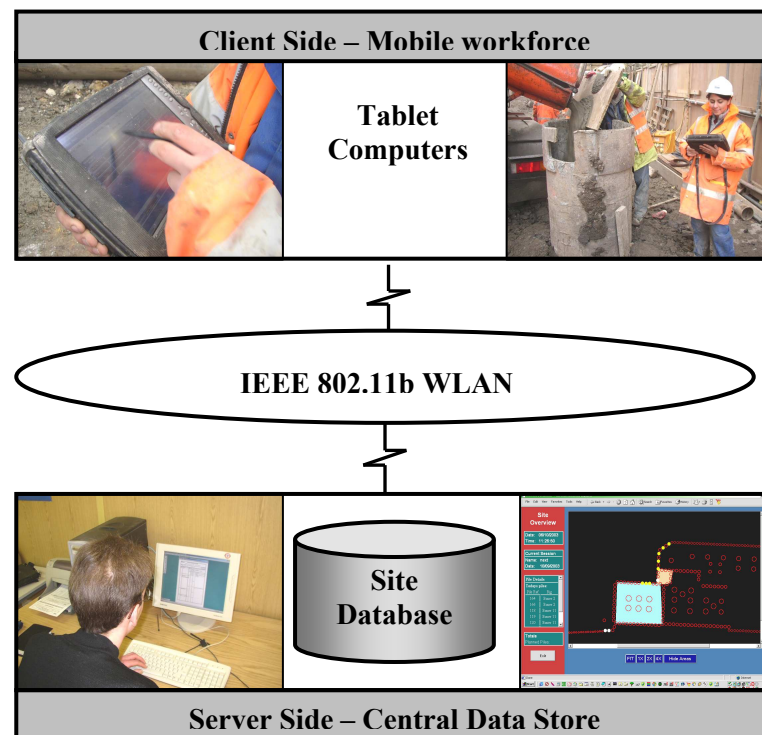


Figure 6: SHERPA system configuration

The outcome was the development of a self-contained Wireless Network Cell (WNC) with the ability to provide wireless coverage to the construction site (see Paper 1). The WNC allows the creation of a cellular site network with each WNC providing wireless coverage to an area of the site. Connection for site users to the server located in the site office was achieved by relaying data through one or a series of WNC (Figure 7).

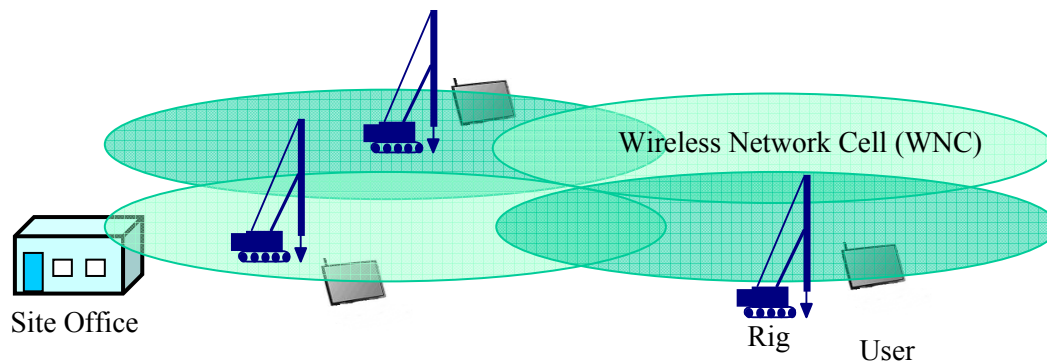


Figure 7: Cellular configuration of the WNC

Two prototypes were created, the Model I prototype (Figure 8), was developed around a steel enclosure with an integrated telescopic mast to deploy an omni-directional communications antenna and mount a small solar panel. Powered by a 12volt, 12Ah sealed lead acid battery and controlled by a 7-day, 24-hour programmable timer switch, Model I was deployed at both Kings Cross and Wembley sites. The WNC were mounted at the periphery of the site and on the foreman's hut to eliminate causing an obstruction and reducing potential damage to the WNC. Following the implementation a number of issues arose regarding the operation of Model I (see paper 2), these were:

- **Signal Penetration** – To allow for easy reconfiguring, all Model I WNC were provided with omni-directional antennas, at the expense of low antenna gain. This resulted in a lack of signal penetration to the centre of the site, especially on larger sites.
- **Power** – Even with the use of a power-saving 24-hour timer switch, the 12v batteries required replacing every 2-3 days. A lack of maintenance on the site and time to replace the batteries by the workforce, resulted in loss of signal when the batteries expired. A larger 24Ah battery which could potentially last for a whole week, was tested on site to remedy the situation, however its practicality was restricted by its weight (9 Kg). The use of a small solar panel to increase the operating time of the WNC through trickle charging the battery was found to be suitable only in direct sunlight when the full 350mA output could be achieved. This was reduced to a variable 100mA output in broken cloud and to 30mA in overcast or shadowy conditions proving impractical for use.
- **Portability** - Whilst the units were portable, the emphasis on protection and use of a steel enclosure meant that they were bulky to handle and relocate around the site.



Figure 8: Model I design with solar panel and located on the foreman's hut

The problems identified during the implementation of the Model I prototype, directly led to the development of the Model II prototype (see Figure 9). Model II was designed around a smaller form factor crush-proof, watertight casing with a separate connection for power and the antenna. This not only reduced the weight of the WNC but also allowed for a separate battery holder, or a connection to be made to the 175Ah rig battery, increasing flexibility in deployment around the site (see Paper 2).



Figure 9: Model II WNC prototype design and installation on a piling rig.

Locating the WNC on the piling rig, effectively allowed for the creation of a roaming WNC within the site, which would in-turn provide network coverage around the rig, where the majority, if not all of the data capture was carried out.

4.4.2.2 Server-side development

For rapid implementation and development, a MS 2000 Server operating system and MS Access database were installed on the site server. The use of off-the-shelf server software allowed for easy implementation of a thin-client application and database development. Thin-client access could be provided to the database for multiple users, over the WLAN from both the site and the site office using the MS Terminal Services Client (MSTSC) protocol.

4.4.2.3 Site data capture interface

A two-level MS Access database was created for the capture of site data (see Paper 1). Pile design details including levels, volumes, cage designs and concrete mixes, were entered using a management interface allowing for the creation of a single data source. For data collection, a process orientated set of data entry pages were created for use by the workforce (see Figure 10). This comprised a series of tabbed pages to record pile construction details at the point of delivery, based on the information processes observed during research cycle A.

Figure 10: Tabbed user interface with built-in data verification.

Underlying data verification logic was built-into the interface to provide verification to the users as the data was entered (see Figure 10), highlighting any potential non-conformances to users and to ensure the construction of a sound pile. In addition, the ability to graphically visualise the integrity of the pile during concreting operations was provided (see Figure 11). All data entries were time stamped within the database and related to a specific user logon, this coupled with the ability to lock-off individual data capture pages helped maintain the integrity of data.

The use of a WLAN enabled all data to be stored in the site server directly after entry. On completion of the pile, data could be readily accessed by the site engineers to produce electronic pile log reports and soil profile logs.

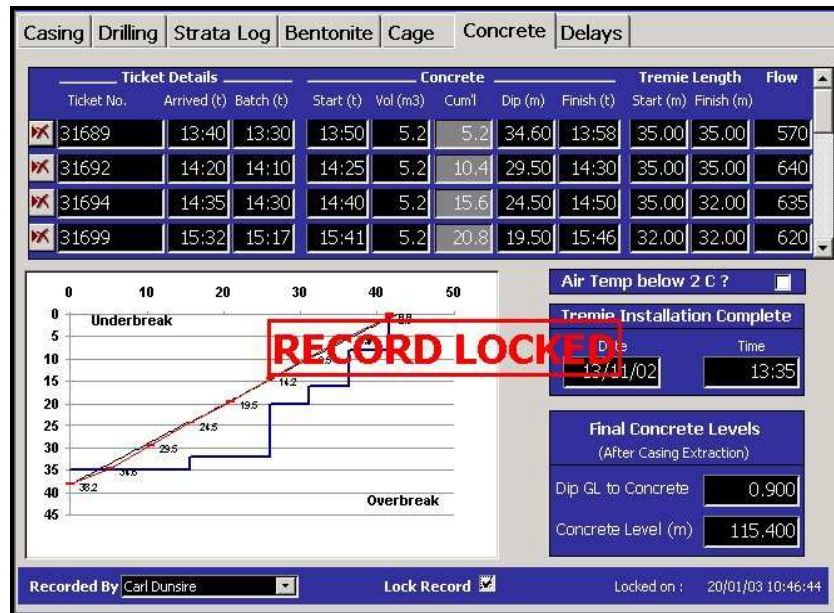


Figure 11: Visualisation of concrete entry with page locking.

4.4.2.4 Site data capture hardware

The users hardware specification observed from research cycle A was further restricted by the requirement for the device to communicate with the selected IEEE 802.11b protocol. This coupled with the fact that manufacturers were developing smaller PDA type equipment, dramatically reduced the selection of available devices.

A semi-rugged device was selected for use in the system, one of few available devices with the ability to integrate the IEEE 802.11b protocol within the unit and include a MS terminal services client (see Figure 12). Another key driver in the selection of the device was the difference in cost compared to fully rugged devices, typically £900 per unit compared to £3000-£4000 per unit. Key factors in the decision to use the semi-rugged unit were:

- more devices could be purchased for the equivalent expenditure;
- this was a prototype system;
- better devices were likely to emerge in the next one or two years; and
- the unit would be expected to last for one year compared to three or four years for rugged devices, allowing for better return on investment.

4.4.2.5 Data management

The emphasis on communication with a central data store and data capture by the site workforce within research cycle B required the development of a database to store the pile schedules and standard contract specification settings for verification of the data input on the site (see Paper 1)

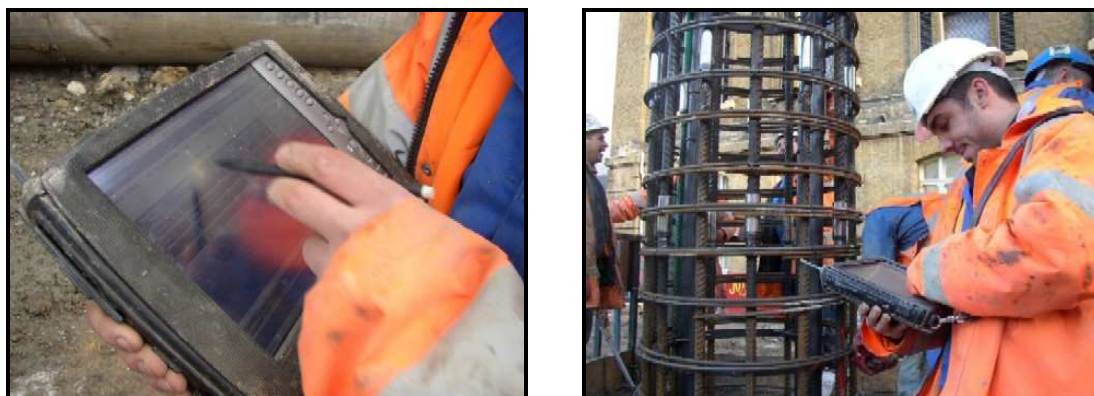


Figure 12: Windows CE touch-screen tablet computer in operation

4.4.3 IMPLEMENTATION

Following the development of the three-tier system, two sites were identified by SFL for implementation (see Paper 2), these were:

- Kings Cross/St Pancras Underground Station Redevelopment; and
- Wembley, National Stadium Redevelopment.

During implementation, the following differences emerged between the two contracts, which would prove to have a bearing on implementation and further development.

- Users – the type of user undertaking the data capture;
- Type of work – the type of piling work being carried out and contractual requirements for data recording;
- Daily output – the number of piles being constructed per day; and
- Site attributes – the physical size of the site.

The technical nature of the work at Kings Cross, large diameter piles up to 2100mm in diameter and up to 40m deep using support fluid were to be constructed. This dictated that full-time management and control of the piling operations was needed, as such specific ‘pile managers’ were utilised to monitor the pile construction and undertake all data collection duties. The daily output at Wembley (approximately 30-40 piles per day compared to 2-3 at Kings Cross) together with the less technical nature of the piling works, meant that the site workforce could be utilised for data capture duties.

4.4.3.1 Operation of site wireless network

The operation of the WNC proved to be a successful data capture enabler for the SHERPA system with core features identified as flexibility, scalability and ease of deployment. The number of WNC deployed on Kings Cross was two, compared to six at Wembley. Whilst this difference was a direct result of the size of the site, it was also influenced by the volume of demolition work, dispersion of workforce around the site and location of the working areas handed over to SFL.

The Model I prototype was initially deployed at both sites with the intention of being located on the site boundary. However, physical site factors such as: size of the site; creation of spoil heaps; different working levels around the site; movement of plant and machinery; construction of superstructure; and location of site offices required that the WNC be relocated towards the centre of the site (see Paper 2). These issues were addressed with the development of the Model II prototype allowing for more flexible

deployment around the site, and the utilisation of more advantageous positions such as tower cranes (Figure 13).



Figure 13: Model II WNC prototype located on tower-crane

Security of WLAN has been a particular problem, in some cases resulting in the ban on wireless networks, particularly in sensitive locations (Knight, 2002). Whilst the 802.11b standard includes an encryption method, wired equivalent privacy (WEP), based on the RC4 algorithm this has been cracked and offers insufficient protection against attack. However, there still exists a number of solutions that can be used to further secure WLAN's, these being:

- turning off the broadcast of Server Set Identifiers (SSID);
- not using default settings on the WLAN equipment; and
- installing proprietary security measures such as firewalls.

All SHERPA wireless networks have a unique SSID, the broadcast of which is turned off. Site-office wired networks are used primarily on larger long-term contracts and often include links direct to the head-office. In such cases, it is envisaged that firewalls would be implemented between the SHERPA server and the corporate network.

4.4.3.2 Site data capture system

On-site, one-to-one training was given to field operatives at both Kings Cross and Wembley by working with the site users throughout a series of days and teaching them how to use the system during their work. Whilst the low output and specific data collection and monitoring task of the pile managers at Kings Cross allowed users to be quickly trained, the increased emphasis on output and use of SHERPA by the workforce during their normal working duties extended the period of training at Wembley.

The tabbed user interface was designed specifically to: allow all users on any site to undertake data capture without need for alteration or specific interface development; and ease implementation between sites, eliminating the need for re-training and further interface development. The system was successfully deployed at Kings Cross, however, the less detailed contract requirements at Wembley, simpler data collection needs and division of site data collection duties between the workforce resulted in site managers and users requesting less detailed pages specific to their duty. As a result, three further interfaces were developed for simplified data collection as follows.

- **Rig Interface** – Designed for use by gang A, this included simplified data capture pages for the casing, drilling and cage processes (see Figure 14).
- **Concrete Ticket Interface** – To overcome the difficulties with utilising barcodes, the site concrete technician was provided with a tablet computer to record concrete delivery ticket details such as ticket numbers, delivery times and slump records. This would assist in the integrity of data capture by allowing the site users to select the previously entered ticket detail from a drop-down list.
- **Concrete Gang Interface** – Designed for Gang B this interface allows the concrete ganger to select a concrete ticket entered by the concrete technician and apply the details to a specific pile, thereby eliminating data re-entry (see Figure 15).

Structure: B1 ZONE 10

Casing Drilling Strata Delays

Start Drilling Start 23/05/03 15:34

Rig Name

Target Toe Dip (m)

Top of Casing to Toe (m) 29.200

Finish Drilling Finish 23/05/03 22:24

Menu

GET PILE

L17
Bearing Pile

Scheduled Details

Diameter	600
Platform	46.000
Toe	17.000
Cut-Off	43.775
Cage	45.055

Figure 14: Simplified rig interface developed for the Wembley contract

One common difficulty encountered by all mobile workers was the lack of battery power on the tablet computers (see Paper 2). Although users were provided with on-site chargers and replacement batteries they were unable to effectively control this whilst operating on the site. Whilst the ‘thin-client’ nature of the system restricted any data loss in such circumstances, replacing batteries during work was frustrating to users and risked user acceptance of the system. In addition, the nature of the Windows CE operating system required that the WLAN drivers were required to be installed into the memory of the tablet computers. This caused major difficulties when battery power was lost, requiring users to return the tablet computers to the site office for re-installation of the WLAN drivers before access could be re-established with the site server and database.

Pile Ref: L17 Dip to Cut-Off: 3.225

Ticket No.	Start Time	End Time	Volume	Dip (m)	Tremie (m)
125699	00:00				0.00

Ticket No.	Start	End	Volume
1234	15:39	15:39	3
1234	15:38	15:38	3

Ticket No.	Volume	Split ?
0	0	
125698	6	
125699	6	
125703	6	

Buttons: Get File, Return, Cancel

Figure 15: Simplified concrete gang interface with ticket pop-up

4.4.3.3 Server-side Operation

The main difficulty arising from the deployment of the SHERPA system was the relationship between MS 2000 server software, the wireless network and the tablet computers. Two main factors emerged that significantly affected the operation of the system, these were:

- the nature of the wireless network, especially on the construction site, may cause the server to lose sight of the client for short periods of time; and
- the tablet computers losing battery power and hence state.

Any or both of these factors could cause the server to lock users out of the system, this, coupled with the limited number of user licences, increased the management burden of the system over that reasonably expected.

4.4.4 INTEGRATION

Observations from research cycle A, dictated that the main drivers within research cycle B would be the use of a consistent data set and an improvement in communication of data between the workforce, ultimately leading to an improvement in construction quality, as such, limited integration was achieved.

However, some limited integration with the client was achieved at Kings Cross through the provision of electronic pile logs which were generated from the database and transferred into PDF format and posted onto the project web portal. In addition, the contract required the generation of soil profile logs for each pile. To achieve this an off-the-shelf geotechnical database was purchased (HoleBase) in which a standard borehole log was designed. Transfer of data from SHERPA to HoleBase was achieved through the creation of an intermediary text file using the Association of Geotechnical and Geo-environmental Specialists (AGS) format, which could be directly read by HoleBase, enabling the generation of pile bore records to BS 5930 (Figure 16).

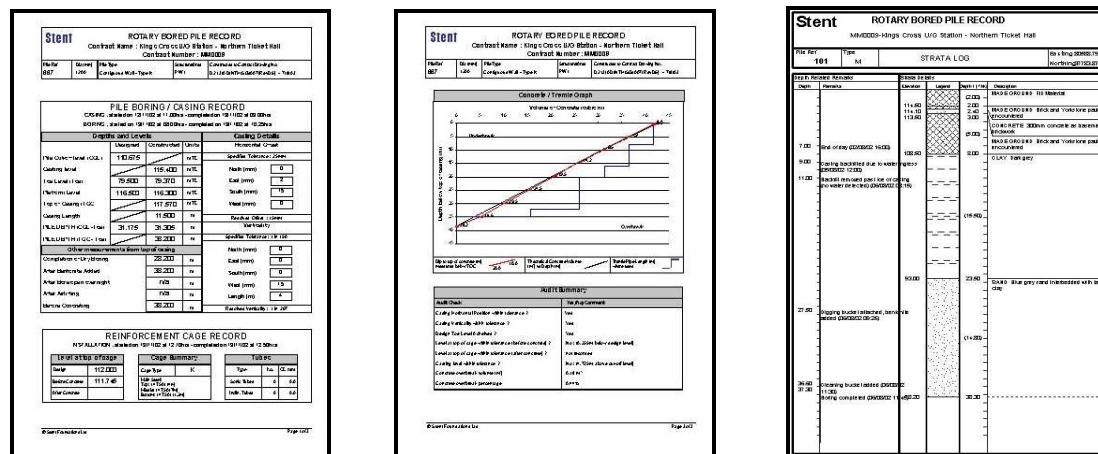


Figure 16: Electronic pile log and soil profile log to BS 5930

4.4.5 OBSERVATIONS AND REFLECTIONS

From systems engineering, implementation and integration work undertaken within research cycle B, the following observations and reflections were made:

- Replacement server software** - One of the main difficulties identified with implementation of the SHERPA system were those caused by connection to the server. This not only increased the management burden on the site but also risked the loss of user confidence in the system at a crucial stage. Due to this, replacement server software or further server development should be carried out.
- Flexible user interface** - differences in data capture requirements between Kings Cross and Wembley (see Papers 2 and 3) suggested that a flexible system be adopted to allow site managers to tailor data capture to contract specific requirements such as personnel, type, volume of piling and contract specifications.
- Integration and access to data** - the use of the MS Access database with limited server licences effectively restricts the ability to share data within the site office and externally from the site. Therefore an alternative, non-restrictive mechanism was required to improve the accessibility and integration of site data both on and off site.
- Improved battery life** - changing batteries on site during the working day is not practical, especially for the general workforce who tend not to leave site throughout the day. Therefore, some form of improved battery power or device management was required for the tablet computers.
- Reduced cost of ownership** - Whilst the cost of tablet computers and WNC would be dependent on factors such as the size of the contract, a significant cost to all contracts would be the requirement for server software and terminal services licences. As the server was posing the main difficulties within the system, suitable cost-effective alternatives should be investigated.

4.5 RESEARCH CYCLE C - ENHANCEMENT

Research cycle C comprises four phases, investigation, systems engineering, implementation and integration and is based on the observations and reflections from research cycle B.

4.5.1 INVESTIGATION

Many examples of web-based technologies aimed at improving communication, collaboration and information exchange between project participants, can be found within the construction industry, these include:

- web-enabled project management systems;
- company extranets and intranets;
- performance monitoring systems (Cheung, et al, 2004);
- design management extensions (Augenbroe, et al, 2002; Veerami, et al, 1998);
- supply-chain integration; and
- e-commerce.

Such systems use a variety of tools and technologies such as e-mail, document management, CAD and digital cameras and they facilitate the sharing of data by different parties at all stages of the construction lifecycle from design to final inspection.

The most extensive use of web-based systems within construction involves web-enabled project management systems (WPMS), (Dawood, et al, 2002; Deng, et al, 2001, Lam and Chang, 2002; Tam, 1999). WPMS incorporate a variety of tools and technologies, using the communication capabilities of the web to store, share, manipulate and control project information and documentation in a distributed environment. They have been shown to provide a number of benefits (Alshawhi and Ingirige, 2003; Mohamed and Stewart, 2003; Thorpe and Mead, 2001) many of which align closely with the problems encountered within this research, these include:

- the elimination of paper-based reports, reducing printing, posting and storage costs;
- a reduction in site visits through the use of up-to-date digital photographs or web-cams;
- a reduction in delays from awaiting late or missing information;
- the avoidance of mistakes from the use of out-of-date information; and
- more accurate information transfer between project participants.

These factors, together with the ability to provide net-distributed applications and access for remote and site-based users through a standard web-interface offers a desirable and proven alternative to the original MS Access based system.

4.5.1.1 Replacement server software

Investigations into suitable replacement server software were governed by the following two key factors.

- **Cost of ownership** - to reduce ownership costs, open-source software can be used. Generically, open source refers to a program in which the source code is available to the general public for use and/or modification from its original design, free of charge. Open source code is typically created as a collaborative

effort in which programmers improve upon the code and share the changes within the community. Open source sprouted in the technological community as a response to proprietary software owned by corporations such as Microsoft.

- **Dynamic content** –web pages can be made more dynamic and interactive, through the use of scripting languages of which there are two types: server-side and client-side. Server-side scripting performs all of its processing on the web server and delivers a final product (the web page) to the user's browser. Client-side scripting does all of its processing on the user's own computer and is commonly used to create pop-up windows, pull-down menus, calculations, and mouse movement effects (i.e., menus or images that change when the user's mouse passes over them).

4.5.1.2 Mobile computing and web technology

There are currently three market leaders of mobile computing operating systems, these being Palm (utilising Palm OS), Windows CE (based on Windows technology) and Symbian EPOC (originated by Psion), each offering their own interface and integrated software. There is also a considerable amount of third-party add-on software available through shareware, freeware or by direct purchase for each system.

However, one factor common to all operating systems is the inability to use software across platforms, without purchasing two versions of the software, which then may or may not be fully compatible without a third party conversion package. This forces site data capture system providers to initially make a choice of platform, which invariably restricts the availability of software and the choice of hardware available to support the software.

One main driver for the adoption of mobile computing has been the ability to connect to the Internet from anywhere, hence one common factor between mobile operating systems is their use of web-browser technology. The possibility of utilising the web browser for site data collection potentially provides the following benefits:

- platform independence;
- increased number of devices to choose from;
- allows real-time data collection;
- limited or no on-device data storage, increasing data security; and
- easier access and sharing of data;

4.5.2 SYSTEMS ENGINEERING

This work phase resulted in the conversion of SHERPA to a web-based data capture system whilst maintaining the three-tier approach utilising client-side data capture, a wireless network and site-based server (see Papers 3 and 4).

4.5.2.1 Server-side development

An open-source web-based architecture was selected to replace the MS Access database and server software with a MySQL database and Apache web server respectively (see Figure 17).

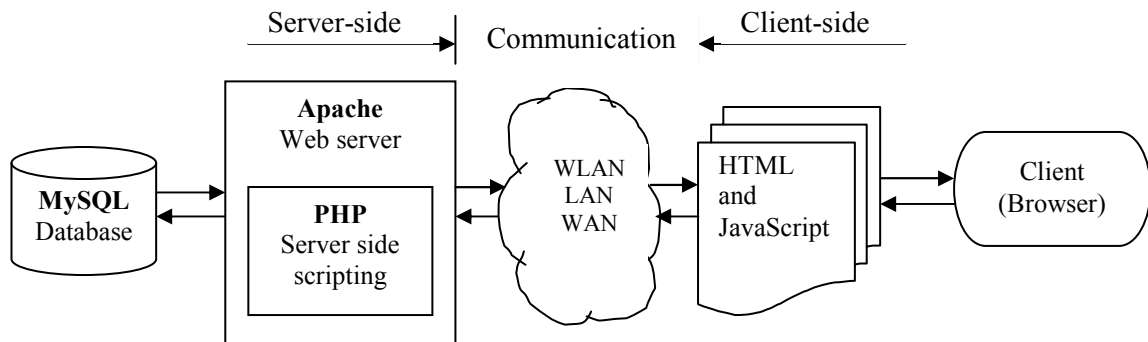


Figure 17: Architecture of the web-based SHERPA system

The Apache web server and MySQL database were installed on the server within the site office, together with Hypertext Pre-processor (PHP) an open-source server-side scripting language to provide dynamic content to web-pages (see Papers 3 and 4). The main drivers behind the selection of PHP were:

- its compatibility with many operating systems including, Linux, Unix, MS Windows and Mac OS. Potentially allowing for future development using an open-source operating system;
- it can be supported by many web-servers including, Apache, MS Internet Information Server, Personal web server and iPlanet server; and
- it allows for connectivity to a variety of databases including; MySQL, Adabas, dBase, Oracle and many other databases using open database connectivity protocol (ODBC).

JavaScript was selected to provide client-side interaction because it allows for object-oriented programming and uses much of the same programming concepts as C++ and Java. Both JavaScript and PHP are interpreted languages, meaning that unlike the majority of desktop applications no executable file is generated for a specific computer or processor. Instead, the code is compiled only as and when it is required. The Apache web-server compiles the code on the server-side whilst JavaScript is interpreted on the client-side browser. This means that the code can be written once and utilised on many computer platforms and by a variety of browsers including, Netscape Navigator, MS Internet Explorer and Opera. Whilst interpreted languages are slower than compiled programs and have in the past been limited by computer processing speed, the advantages to be gained from improved accessibility, ease of programming and system maintenance together with modern faster processing speeds makes this a viable choice for implementation.

4.5.2.2 Site data capture interface

The philosophy of a two level system for data management and data capture was transferred into the web-based system, the main difference being the ability to create dynamic content via PHP (see Papers 3 and 4).

To address the requirement for a flexible user interface that could be tailored to meet contract and personnel requirements on the site, two sets of web-based data capture pages were created. This comprised of a detailed and simple page for each identified RBP information process and where possible pages were mimicked from research cycle B. A system of data profiling was devised to allow site managers to select from one or a number of data capture pages to create a profile that could be applied to any user logon (see 4.5.2.4).

The site data capture interface is divided into three distinct parts: navigation bar; menu bar and data entry section (see Figure. 18).

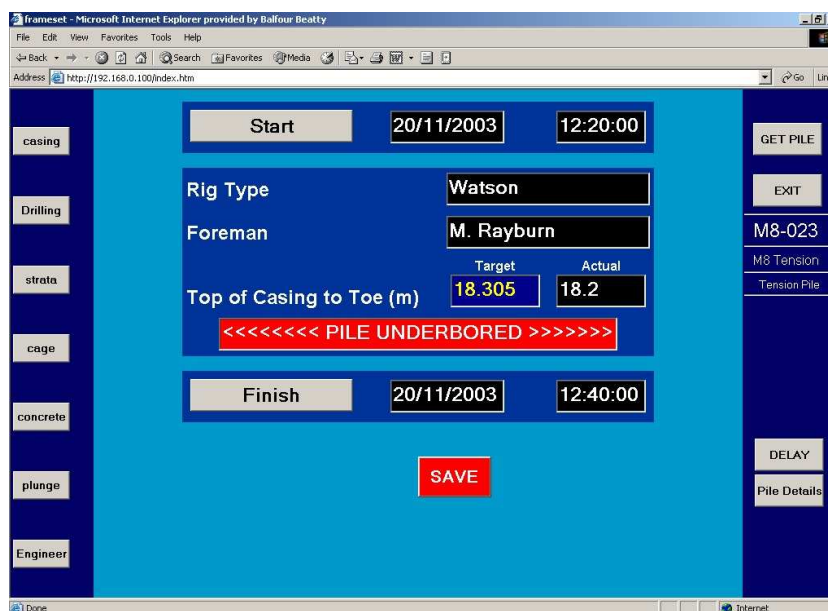


Figure 18: Web-based data capture interface

Located on the right hand side of the screen, the navigation bar allows users access to the pile selector from which they can request the latest pile design details from the server for the current pile. Once a pile is requested the design details and construction tolerances are embedded within the navigation bar allowing them to be accessed by all data capture pages for data verification purposes through the use of client-side JavaScript or to be viewed by the user as required.

The menu bar is located on the left-hand side of the screen and is a direct replacement for the tabs previously used. The menu is a set of dynamically generated buttons, each button relating to either a detailed or simplified data capture page depending on the data capture profile of the user. On pressing a button, the relevant data capture page becomes visible in the centre of the screen. The nature of web pages requires that the saving of the data for each individual page is controlled by the site user. An alert message is thus used to confirm that the user has saved the data from the current page prior to changing pages.

In keeping with the original development, the pages have been designed for touch-screen operation and include pop-up boxes for date, time and number entry together with pop-up select lists generated from standard contract details or concrete deliveries. The underlying continuous self-auditing process has been maintained to alert users and check for possible non-conformances.

4.5.2.3 Site data capture hardware

The use of a web interface allowed the existing tablet computers to be re-used via the in-built MS Internet Explorer for pocket PC, which also had integrated JavaScript support. To solve the problem with loss of power, rechargeable external battery packs were purchased to provide an additional 10 hours power over the existing internal batteries. The packs comprised 10 No. 4100mAh, 1.2v NiCad batteries which were shrink wrapped and provided with a fly-lead for direct connection to the DC input on the tablet computers (see Figure 19).



Figure 19: Tablet computer with additional battery pack

Once the battery pack was drained, the tablet computer would automatically switch to the internal battery pack for an additional four hours, if required. To facilitate ease of use, the battery packs were fixed to the back of the tablet computers with Velcro.

4.5.2.4 Data management

A new management interface was developed to allow for further integration and re-use of data beyond that achieved in research cycle B.

To address the requirement for a flexible user interface a system of data profiling was used, allowing for the creation of specific interfaces for data capture and access to the data management system. Data capture profiles are created by selecting one or a number of data pages from either the detailed or simplified page set, which can then be applied to a specific user login allowing site managers to dictate what data collection they require on each site, how access is managed, who has what access and how complex the data collection should be for each individual process. (see Figure 20).

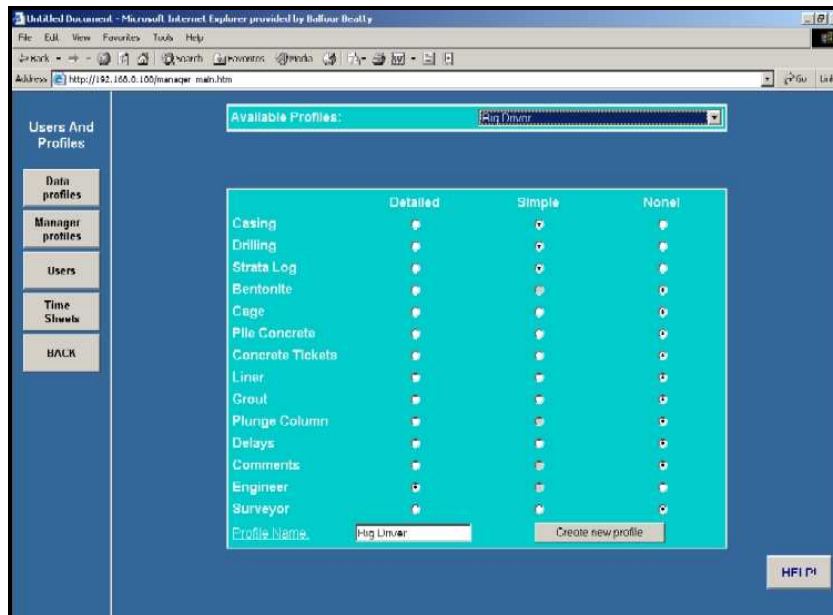


Figure 20: Web-page for the creation of data capture profiles

The data management interface was divided into a number of sections, access to which is governed by the use of management profiles. Similar in functionality to data profiles, management profiles are created and administered by the project manager and once created can be assigned to specific user logins for both on and off-site access.

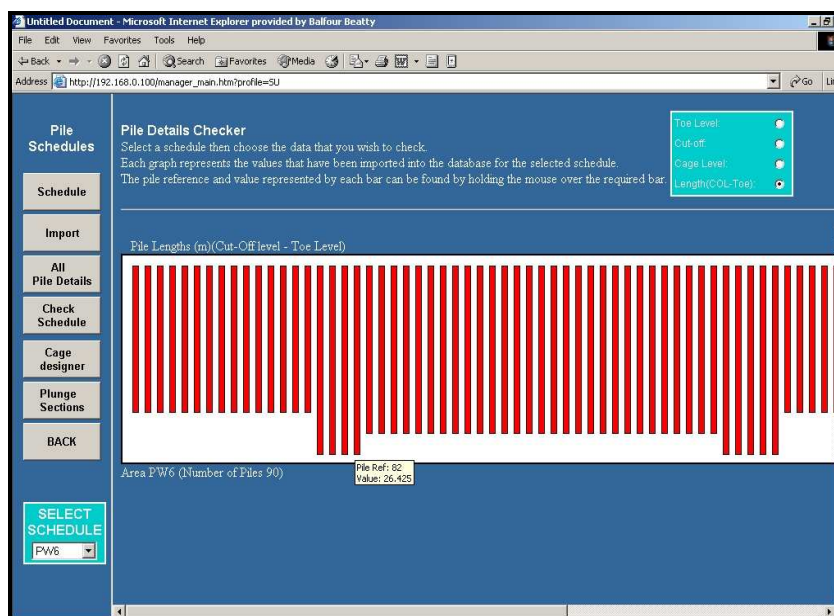


Figure 21: Histogram visualisation of imported pile schedule data

The data management interface is similar in structure to the data capture interface and has two sections: the menu bar and the main screen. The menu bar is a set of

dynamically generated buttons created for each user based on their management profile, it is located on the left-hand side of the screen and has been designed to maintain a level of consistency for users who migrate between both services. The main screen is multifunctional and allows for data entry, management, reporting and visualisation of data (see Paper 4).

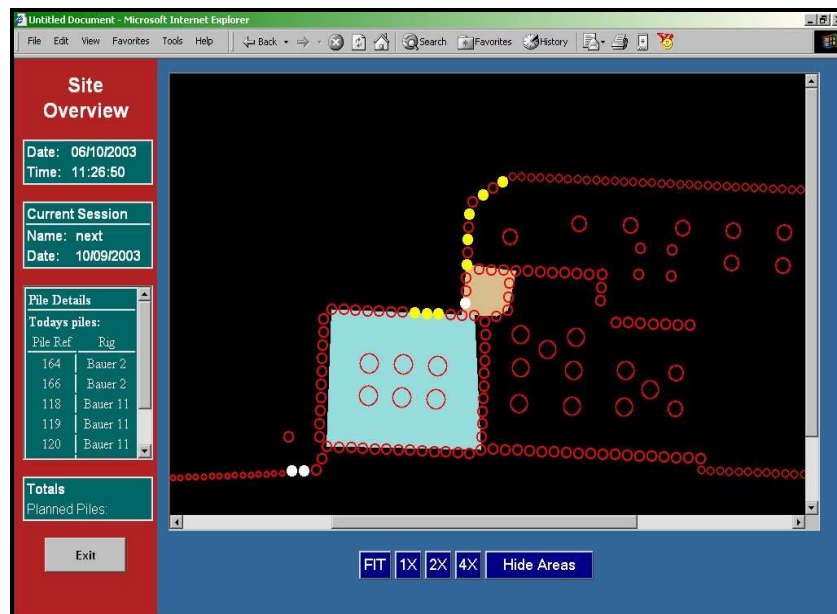


Figure 22: Visualisation of site progress through 'site-viewer' tool

The use of a web-based architecture allowed for the development of a number of additional tools to facilitate the re-use and visualisation of data, as follows.

- **Design schedule management** – multiple schedules can be imported directly into the database from spreadsheets and a one-to-many relationship is maintained between schedules and pile design details. In addition, a schedule visualisation tool has been implemented to assist in the rapid verification of imported data using a histogram representation of critical design elements such as pile length, toe level, cut-off-level and cage level (see Figure 21). Each line of the histogram represents one pile, with the length representing the data value to be checked. On discovering a possible erroneous value, both the pile reference and value can be obtained by floating the mouse over the relevant histogram line.
- **Reporting tools** – allows for the collation and viewing of construction data in HTML format including pile logs, concrete delivery analysis and quality audit reports.
- **Site viewer** – The site viewer dynamically generates a colour-coded 2D representation of the current site status using the coordinates and diameter of each pile contained within the database. The image created includes a pan and zoom function and colours each pile according to its current status: concreted; completed; or incomplete. Each site view image is augmented with an underlying 'click map' allowing additional pile data to be accessed by clicking on the required pile via the use of a right-click menu (see Figure 22).

- **Planner and sequencer** – similar in functionality to the site viewer, the planner allows managers to utilise a 2D click-map representation of the site to generate and step-through proposed construction sequences.
- **Cost analysis** – A prime cost analysis for materials, plant, labour and steel can be produced based on pile production for any day or period during the contract. Income is calculated by pre-processing the tender and assigning plant, labour, concrete and steel values to each pile, whilst costs are recorded through the daily input of timesheets for labour, plant returns, concrete and steel deliveries.

4.5.3 IMPLEMENTATION

The web-based system was deployed on the following sites in London:

- White City Retail Development; and
- Arsenal Stadium ‘The New Highbury’.

Similar to implementation within research cycle B, both sites were of differing size with White City comparable to Wembley Stadium. The type and volume of piling work on both sites dictated that data capture would be carried out by the workforce with no use of pile managers on either site. A distinct difference in the White City contract dictated that the piling works be carried out as a joint venture with Cementation Piling and Foundations Limited (CPL). This would involve training and acceptance of the system by staff from a company other than SFL. To recover expenditure on the SHERPA development carried out, SFL effectively rented the SHERPA system to the White City joint venture for the period of the contract.

4.5.3.1 Operation of the site wireless network

The Model II prototype of the WNC was successfully deployed on both sites utilising rig based WNC and tower cranes to propagate the signal across the site. Additional factors affecting the implementation of the WLAN in the early phases of the site were observed as follows:

- the location of the site office may not be known;
- piling areas may not be known;
- the site is chaotic in nature; and
- power and communications to the site office may not be in place.

4.5.3.2 Site data capture

All users were provided with on-site training in the use of the system, with previous users readily adapting to the web-based system. At White City, training was provided to users from both companies, with some resistance observed from CPL users who initially saw the system as being imposed by a competitor. However, this resistance reduced as CPL workers observed the system being operated by SFL staff.

All users at Arsenal were new to the system which, when added to the early chaotic nature of the site resulted in a protracted implementation and training phase. In addition to this the following personnel related factors affected the speed of implementation at Arsenal:

- literacy of users;
- transient nature of site staff;
- reduced site staffing levels caused by illness; and

- level of enthusiasm instilled by the foreman on site staff.

Personal adoption of the tablet computers was observed on both sites with users requesting specific tablet computers at the start of each working day. In addition to this, site users developed a series of lecterns on which to mount the tablet computers (see Figure 23). This resulted in the removal of a personal connection with mobile computer to the placement of the computer at the location of work, which could be used by a number of personnel as and when required.



Figure 23: Operation of tablet computer mounted on lectern

4.5.3.3 Data management

All server connectivity problems observed in research cycle B were eliminated with both the Apache web server and MySQL database performing well on both sites. The web-based management side proved easily accessible to more site-based personnel. In addition to this, user comments and suggestions for improvements and additional reporting were forthcoming, effectively providing a driving effect within the company for future development and implementation of the system.

4.5.4 INTEGRATION

This section discusses the additional integration achieved over that in research cycle B.

4.5.4.1 Site integration

The integration of data at site level was significantly improved beyond that of pile record generation observed in research cycle B. This was most apparent on larger contracts such as White City, where there were a larger number of site engineers, driving for further integration and re-use of site data. The web-based architecture allowed any engineer to access the system ‘licence-free’ utilising a web-browser on any machine within the site office. The operation and control of the system was undertaken

by the site staff, with specific tasks such as schedule importing, quality auditing, pile log generation, profile management and concrete delivery analysis assigned to a number of staff, work that was carried out by a single site engineer on smaller contracts such as Arsenal.

Better understanding of the site progress was achieved through the use of the site viewer, which enabled site managers and engineers to visualise the progress on the site and help eliminate ‘missed piles’, which would result in additional costs from revisiting site. The integration of productivity and prime costs allows engineers to get a 90-95% accurate picture of the current financial status of the project, through the generation of profit and loss tables (see Paper 4) and graphs for any period throughout the contract (see Figure 24).

4.5.4.2 Site worker integration

Currently, many construction workers are excluded from the information loop providing guidance on current site progress in terms other than production or work scheduling. This is particularly true of financial information, which many companies see as sensitive. Such an approach reinforces the ‘them and us’ attitude between site workers and their *knowledge worker* counterparts. SHERPA aims to redress this balance by allowing site managers to produce a variety of reports and graphs that can be distributed to the site workers such as analysis of production by rig or working gang and graphs showing the relationship of profit versus productivity. Such reports can be used to provide better awareness without providing commercially sensitive information to site staff, some of which may be temporary or agency based.

4.5.4.3 Company integration

Direct server access for off-site personnel can be gained via the SFL corporate network or through the use of a static IP address on the server. In both cases and for practicality, the site has to have a minimum 256k Asymmetric Digital Subscriber Line (ADSL). The use of ADSL may be affected by the following factors:

- the availability of the service for the geographical site location;
- the location of the site office within the site;
- the duration of contract; and
- capacity for forward planning within the contract.

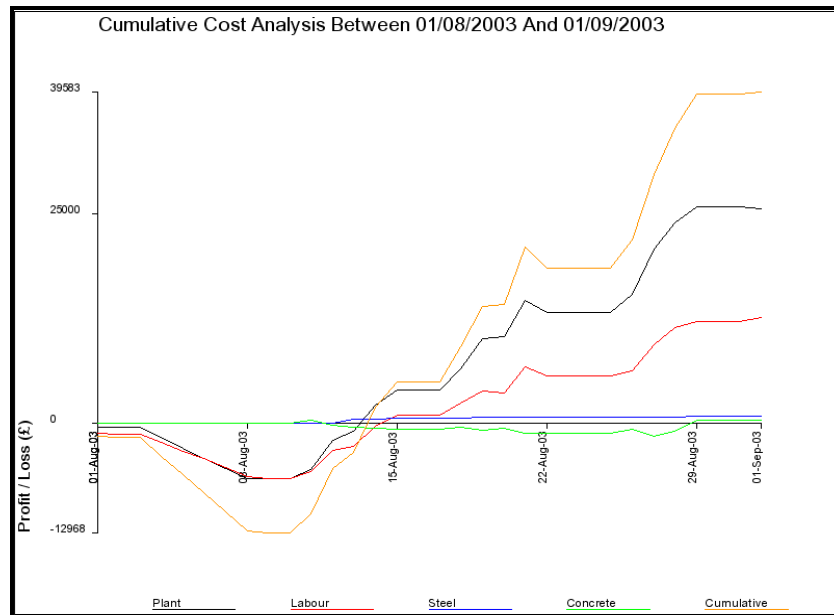


Figure 24: Prime cost analysis graph for contract period

Where ADSL is not provided, the web-based nature of the SHERPA system allows for the creation of a 'mirror' service located at the head office. Data can be sent from the site to the head-office on an hourly, daily, or weekly basis via a minimum 28Kbit/s general Packet radio Service (GPRS) connection, allowing at best a near real-time view of site progress and access to site data. Whichever communication protocol is used, the web-based system allows for greater distribution of the data throughout the company utilising a common interface and system management tool.

4.5.4.4 Data analysis and business process integration

Data integration at both site level and office level was primarily targeted at production and contract control. However, there exists the opportunity to inform the business at both the strategic and tactical levels through the analysis of data captured on the site. Analysis of concrete usage from both the RBP and CFA processes has been carried out (see Paper 5). Current expenditure on concrete within SFL is approximately £15 million per annum equating to approximately 30% of company turnover, therefore any savings from waste or improved process management in this area has the potential to impact on company profitability.

4.5.4.5 Integration with other contract parties

The impact of SHERPA on the client is related to the ability and desire of the client to accept the use of electronic documentation. Whilst some large contracting companies and consulting organisations have shown an immediate acceptance of electronic records, many still insist on the presentation of paper-based documentation. The production of paper-based records can also be attributed to the contract specification, which typically dictates that paper-based records are made available by noon the day after pile construction. SHERPA provides all clients with the opportunity to access pile records and progress plans over the Internet, however, the majority of clients have requested paper-based documentation, a factor that requires addressing through the modification of construction specifications.

The integration of SHERPA has been limited to the posting of electronic pile records on contracts where web-based project management systems (WPMS) have been implemented by the client. A limiting factor posed by traditional document based nature of WPMS. However, there still remains the potential to further integrate SHERPA into the WPMS such as providing links to the site server with on-click access to views of current progress via the site viewer, or access to the proposed sequence of works.

5 FINDINGS AND IMPLICATIONS

5.1 THE KEY FINDINGS OF THE RESEARCH

5.1.1 TECHNOLOGIES FOR USE ON THE CONSTRUCTION SITE

This section aims to describe the key findings with respect to the technologies implemented within the SHERPA system.

5.1.1.1 Wireless networking on construction sites

The wireless network deployed within the SHERPA system is an expansion of the traditional concept of wireless networks, which utilise a wired backbone resulting in only the computer user being truly wireless and free to roam throughout the coverage area of the network. The ever-changing nature of construction sites dictates that any communication protocol must be available to users at all times at any location and at any phase of construction. One main factor in the success of mobile telephony has been the ability to utilise the mobile phone in such a manner with limited restriction, a factor of the cellular nature of the network and it is this analogy that was used in the development of the WNC. In implementing a WLAN on the site, the following factors should be considered:

- **Signal propagation** – the propagation of a wireless signal is dependent on antenna power, type of antenna used and the number and type of obstructions in the path of the signal. Whilst more powerful antennas can assist in improving signal propagation over longer distances, obstacles can still be created which can severely restrict the operation of the WLAN. The main obstacle to signal propagation is caused by the creation of large spoil heaps, the positioning of which was beyond the control of SFL. This is most apparent on larger brown-field sites such as Wembley and White City, where both demolition and piling works are undertaken concurrently. Due to the nature of the site during implementation, limited superstructure had been constructed. However, at Wembley and Arsenal the signal was able to propagate through up to 5 reinforced concrete walls each wall, 200mm-300mm thick. Whilst metal objects such as cranes, rigs and construction plant are recognised as causing signal diffraction, this was not found to be a significant problem on the site. To assist in signal propagation WNC should be placed at advantageous locations such as tower cranes.
- **Power** – in order to maintain portability to the WLAN, batteries are required. Presently, the cost of Lithium-Ion or Nickel-Cadmium batteries is restrictive (up to £400 per battery pack), consequently sealed lead acid (SLA) batteries have been used. Whilst larger SLA batteries could be used 12v-24Ah to provide a full weeks power to each WNC, the weight of such batteries is restrictive (up to 9Kg), therefore for practicality 12v-12Ah batteries have been used that can provide 2-3 days power for each WNC. Power problems can be avoided by utilising battery power from machinery on the site, which are large enough to maintain a WNC. In addition, these allow the creation of a working network cell around the area in which data capture is likely to be undertaken.

- **Security** – the leakage of signal beyond the site boundary is unavoidable, therefore security measures should be in place. The WEP security protocol built into the wireless network should not be relied upon, however, not relying on default settings, the suitable selection of an SSID and use of proprietary security measures such as EAP, RADIUS and firewalls should be considered.
- **Management** – the relocation of the site offices, different working areas and reliance on the system by the workforce for both quality control and access to data requires that the network must be monitored particularly in the early chaotic phases of the site. The level of management required is directly related to the size and complexity of the site and in some cases may need full-time attention.

5.1.1.2 Touch-screen tablet computers

This research has found that touch-screen tablet computers are an acceptable method for undertaking data capture on the site. Whilst the physical unit size means that the devices cannot easily be carried or integrated with the site worker during their construction duties, this has been overcome by the development of lecterns by the site workforce. Unlike inspection and reporting tasks where mobile computers are in constant use by *knowledge workers* and are a direct replacement for paper-based documentation, the SHERPA system is intended as an assistant for the worker on the site. The primary role of SHERPA is therefore to monitor the construction whilst allowing for consistent data to be recorded by the workforce, resulting in brief visits to check and enter data. Consequently, the use of mobile computing by site workers should be considered differently to that of *knowledge workers*.

In addition, the following factors should be considered when implementing any mobile computing application on the construction site.

- **Device type** – semi-rugged devices have proved to be more cost-effective than fully-rugged devices and have a reduced pay-back period, meaning that companies are not ‘tied-in’ to the technology when newer devices may emerge.
- **Power** – construction workers require power for a full days operation on the construction site. Because of the emphasis on production, they are less likely to leave the site to replace batteries than perhaps a knowledge worker would.

5.1.1.3 Site server

The location of a site-server in the site office poses the following potential difficulties, which should be considered.

- **Location of site office** – the position of the site office on the site can be affected by a number factors including: available site space; the current working area and availability of power. The location of the site office can in-turn affect the implementation of the WLAN.
- **Power availability** – By far the greatest issue regarding the use of a server on the construction site is power. Power to site offices can be via mains or provided by diesel generators, the selection of which is influenced by a variety of factors such as: location of the site office; size of the site; the number of contracting organisations. To eliminate potential difficulties with power, uninterruptible power supplies (UPS) should be used.

- **Communications** – the effective distribution of a web-based system relies heavily on the communications protocols available to the site. These in-turn are dependent on a number of factors including: size of the contract; contract duration and ability to forward plan the implementation of technologies such as ADSL.

5.1.1.4 Open-source software

The use of open-source software has proved to be beneficial within the SHERPA system as it allows the application to be distributed to many personnel without concern for potential cost from additional licences. This is particularly pertinent to server software, which would have previously been required for each site on which the system was implemented.

The use of the web for data capture allows for the system to be utilised at all levels of the company through a web-browser interface, increasing the potential for data re-use. The web-based SHERPA system also increases the potential for data sharing amongst project participants through net-distributed application beyond the site boundary.

5.1.2 SITE IMPLEMENTATION

The main findings regarding the implementation of the SHERPA system on the construction site are discussed below:

5.1.2.1 Site workers

Construction site workers have shown the ability to undertake data capture tasks using mobile computers on the construction site, however it must be recognised that this is secondary to the main work task, for which they are paid. The following factors are recognised as having a significant effect on the successful implementation of a system such as SHERPA:

- variable literacy levels amongst site workers;
- the transient nature of site staff, with a large proportion of agency-based and temporary staff utilised on construction sites;
- site workers are directly influenced by the site foreman, therefore a pro-active foreman will aid system implementation; and
- SFL are a forward thinking company, however, previous failed attempts at implementing site technologies, have led to a sceptical workforce who require convincing of the merits of any new technology.

As the SHERPA system relies heavily on the successful implementation and operation at site level, the question of how to integrate the tablet computers into existing working practices was left to the site users, who through the development of the site lecterns showed the ability to adapt technology to fit their working environment.

5.1.2.2 On-site training

Whilst on-site training is less costly for SFL than conducting off-site training specific site and personnel factors such as; availability of site staff; staff illnesses; production rates; literacy levels of staff; and enthusiasm can all contribute to a protracted training and implementation period on the site. It is recommended that a structured training program on the merits and reasons for undertaking site data capture is provided to all foremen within the company, away from the site. In addition, training should be pre-

planned and incorporated into the working day to avoid potential problems caused by the perceived effect on production.

5.1.3 PROCESS IMPROVEMENTS

The implementation of the SHERPA system has improved the RBP process within Stent and potentially provides for the integration of site data within the company through further data analysis and re-use. Improvements that can be identified from the research are:

- **Consistent data** – the use of a common data source and communications protocol can improve the consistency and integrity of data, reduce duplicity and errors caused by the use of incorrect information. This in turn increases the reliability of data being returned from the site.
- **Quality of construction** – the provision of a self-auditing system that assists the site worker in ensuring the pile is constructed to the specified tolerances has been shown to have a positive impact on the reduction of non-conformances on the site. This has a positive financial impact on the contract and provides the client with greater assurance. In addition, there is the potential for the development of a self-certification culture, relieving the client of on-site inspection duties and therefore saving costs.
- **Improved access** – the web-based SHERPA system improves accessibility to the system not only at site level but also for personnel located in the site office and potentially for other contract parties.
- **Improved understanding** – understanding of the current contract progress by personnel other than those directly involved in the project was previously difficult due to the paper-based nature of the records. Middle and senior managers are now able to access relevant progress and quality data. Additionally, where cost information was previously based on accounting principles, a guide to the financial status of the project in relation to production can be obtained.

5.2 THE CONTRIBUTION TO EXISTING PRACTICE

The RBP process is labour intensive, relies heavily on data captured by the workforce at the point of delivery and unlike other piling processes such as CFA does not lend itself to automation. As built information is not represented graphically nor can it be easily audited. This together with the use of traditional paper-based data capture methods increases the potential for errors caused by inconsistent or incomplete data resulting in a cost increase to both the client and contractor.

The SHERPA system has been shown to be an effective solution to these problems through the provision of a consistent data set and auditing of the pile construction data at the point of delivery. A cost benefit analysis has been conducted which indicates that a significant reduction in remedial work can be achieved through the effective implementation of SHERPA (see Paper 2).

A system such as SHERPA can also contribute to increased trust between the engineer and piling contractor, through improved confidence in the collected data and self-auditing process. Thereby instigating a self-certification culture, which could ultimately

reduce costs for the client. However, historical barriers of trust and restrictive contract conditions may still hinder the full adoption of such a culture.

A key factor in the success of any construction company is the effective delivery of individual projects. There exists immense potential for the re-use of site data to inform business processes at operational, tactical and strategic levels (see Papers 4 and 5). This can be increased by the adoption of web-based technologies, which allow for increased integration of data not only within the company but potentially to other parties to the contract (see Paper 3).

5.3 THE IMPACT ON THE SPONSOR

SHERPA has fulfilled the objectives related to improving the collection and re-use of site data within the RBP process. In addition to this the system has shown that an improvement can be achieved in the quality of construction through the reduction of defective work. Whilst no formal client satisfaction evaluation was conducted, where SHERPA has been implemented it has been welcomed by the client, increasing the potential for further work and enhancing the position of the company within the industry. In addition, clients have been happy to endorse and validate the use of SHERPA within SFL.

Improved accessibility to data both on and off-site allows for a greater understanding of the project progress and provides early indication of potential non-conformances. When coupled with additional data such as costing, SHERPA allows for the creation of a powerful tool to monitor project progress not only in terms of quality but also financially. Analysis of data gathered from sites on which SHERPA has been implemented indicates the potential for process improvement and justification of expenditure (see Paper 4). Further implementation and integration of SHERPA within SFL will result in the creation of a comprehensive project archive which can be accessed by business processes such as estimating and help contribute to the elimination of islands of automation.

A cost benefit analysis has been conducted based on the implementation of SHERPA at Kings Cross (see Paper 2). This suggests a reduction of 75% in the cost of remedial work with a projected saving of £62,000 compared to implementation costs of £20,000. If these savings were extrapolated throughout the company the potential projected savings for SFL based on full implementation of SHERPA are £385,000 per annum. However, it must be acknowledged that such extrapolation is not a sufficient basis on which to begin full implementation, as extenuating factors related to specific contracts must also be considered such as; the quality of contract management; volume and type of piling work carried out; the quality of the workforce, and the emphasis on meeting production rates.

The cost benefit analysis together with the successful implementation of the system prompted SFL to establish SHERPA as a business stream within the company. This has resulted in SHERPA being specified by SFL when tendering for contracts with the costs of SHERPA being covered within the tender. However, due to the initial outlay required for SHERPA, this approach may not be possible on smaller contracts with tighter margins. In such cases, the recovery of revenue from larger contracts may need to be utilised to fund SHERPA on smaller contracts.

The SHERPA business stream established by SFL was directly applied to the tender documents for the White City contract, with the intention of sole use by SFL. However, changes to contract arrangements by the client led to the establishment of a joint venture between SFL and CPL with the intention that both companies would utilise SHERPA. This change in contract requirements, together with the desire by SFL to establish a business stream for SHERPA essentially resulted in the provision of a level of service agreement for the joint venture that would otherwise have not been present.

The nature of the research dictates that testing and de-bugging of the system would inevitably be required at site level. Whilst this was accepted on all other SFL sites, the level of service required at White City increased the pressure for a production level system. This rapid transformation from a research project placed additional pressures on the development of SHERPA most of which were due to a lack of forward planning for the implementation, management and support for such a system, a key factor that has been previously shown to affect successful implementation of site based systems within SFL.

The SHERPA system has now become an integral part of the development culture within SFL and has provided many opportunities for publicity (see Table 6). In addition, Stent Foundations were winners of the Effective IT Award 2004 in the category of 'Best use of Mobile and Wireless'. This together with the fact that SFL are now leaders in the field of RBP data capture highlights the intangible benefits that can be gained from involvement with such a research project.

Table 6: Research project related articles published in trade press

Article	Publication	Date
'Stent scores with the Gunners'	Construction News, pp 22-23.	20-May-04
'SHERPA's for construction sites'	Innovation and Research Focus, page 5.	May-04
'SHERPA conquers paperwork mountain'	Construction News, PP 38-39.	15-May-03
'Wembley Stadium'	Cisco Systems Limited Newsletter	May-03
'Information Revolution'	New Civil Engineer, pp 20-21.	17-Apr-03

5.4 THE IMPLICATIONS FOR WIDER INDUSTRY

A direct benefit from the implementation of wireless technologies on the construction site is the ability to access data in near-real time. Such data could in the future contribute to 4D project models allowing for improved integration between design and construction processes.

Arguments still exist regarding the validity of the comparison made between manufacturing and construction (Egan, 1998). However, it must be accepted that site data is the construction equivalent of production data within manufacturing processes. Whilst manufacturing relies heavily on production data to improve business

performance, in comparison, the level of site data re-use within construction remains small.

This project has been solely based on the capture of data within the piling process, however, the infrastructure and methods of data capture could be applied to the wider construction industry. Whilst the SHERPA model could be applied to individual trades, the greatest potential benefit would be gained from utilising such a system for the majority, if not all site contractors. However, there are a number of fundamental issues (see Paper 3) which would affect how such an implementation could be achieved, these being:

- system configuration;
- integration, collaboration and distribution of data;
- system maintenance;
- financing;
- software development; and
- standardised data collection.

5.5 RECOMMENDATIONS FOR FURTHER RESEARCH

The SHERPA system has been used exclusively at the piling stage of the project which is one of the first trades to commence on many construction sites. Whilst this has allowed for testing of the WLAN during both infrastructure and demolition work, there remains the opportunity to test the functionality of the WLAN during the remaining construction cycle and integrate with other contract parties. The following recommendations are thus made for further research:

- **Collaboration** – The emphasis of the research has been on data capture and re-use within SFL. However, SHERPA allows for the capture of construction data in real-time with the potential to contribute to project models, web portals and collaboration tools.
- **Voice communications** – the potential to utilise the WLAN infrastructure for voice data utilising Voice over Internet Protocol (VoIP) technology were highlighted in Paper 1. However, restrictions on suitable technologies throughout the project prevented this from being investigated further.
- **Integration with suppliers** – the integration of SHERPA with suppliers could be achieved through the use of electronic delivery tickets on concrete and steel which could be scanned by either RFID, or barcode directly into the SHERPA system. In addition steel suppliers could be provided access to the planning and sequencing section of the system to synchronise reinforcement cage deliveries with current progress.

5.6 CRITICAL EVALUATION OF THE RESEARCH

Whilst the potential for integration of SHERPA throughout construction has been addressed (see Paper 3) and the potential for further research highlighted, the research has been undertaken solely within the piling industry. The nature of piling works and the inability to effectively measure as-built work makes the position of piling unique within the construction industry. As such the level and validation of data capture presented within this thesis may not be applicable to other trades on the construction site.

Analysis of the benefits from the SHERPA system has been limited to cost-benefit analysis and measurement of the reduction in defects against company performance, with no direct comparison made between the paper-based system and SHERPA system. The nature of construction is such that direct comparison cannot easily be made between two different sites as other factors such as effective management, productivity, type of staff and potential for contract profit can all have a bearing on the outcome of any analysis. Whilst it is recognised that the benefits from implementing IT systems can be measured in pure financial terms, placing a value on process improvement and accessibility to data is more difficult. In terms of this research, process improvements such as reduction in non-conformances, can be identified, however, improved access and re-use of data can only be measured by the acceptance and delivery of the system within the company.

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APPENDIX – A: PAPER 1

FULL REFERENCE

Ward, M.J, Thorpe, A., Price, A.D.F. and Wren, C. (2003). SHERPA: Mobile wireless data capture for piling works, *Journal of Computer Aided Civil and Infrastructure Engineering* **18**(4), pp 200-220.

ABSTRACT

The construction of rotary bored piles uses two inter-dependent site processes, requiring real-time information sharing between the workforce. This is currently achieved through manual recording of data and calculations on site, which can result in errors in pile construction, delays in the construction program and additional costs from remedial works. This paper describes the Stent Handheld ElectRonicPiling Assistant (SHERPA) which utilises workforce driven mobile computers accessing a centrally site-located database through a mobile Wireless Local Area Network (WLAN). The WLAN utilises the IEEE 802.11b protocol for wireless communications, which is becoming increasingly popular in the replacement of traditional wired networks within buildings. However, the application of such technology to construction has been restricted by its use of a wired Ethernet ‘backbone’, which is impractical for the construction site. This problem has been addressed through the development of Wireless Network Cells (WNC’s), which provide a portable and scalable solution to the challenges of implementing mobile networks for real-time data capture in the site environment.

1 INTRODUCTION

Unlike the majority of construction processes piling is unique in that as-built information is not often presented graphically, nor can it be easily audited. The industry relies on text based pile records completed by the workforce, which become the quality documentation providing evidence that the pile has been constructed to the specification. It is therefore essential that data relating to the construction of each pile is accurately recorded at source and during construction activities. Within rotary bored piling, this is currently achieved by using a paper-based system that is completed by the general workforce.

1.1 PROBLEMS AND CHALLENGES

The current problems associated with the traditional data capture practices are:

- Piles are constructed in five distinct phases by two working gangs. Gang A excavates the pile and gang B installs the reinforcement and concrete. Both rely on a shared paper based pile schedule, with gang B also reliant on data recorded by gang A.
- Methods used for recording the pile information duplicate effort and potentially place the integrity of the pile at risk. Data transfer errors made from the schedule or mis-calculations during pile construction can result in non-conforming piles being constructed leading to additional costs, delays and client dissatisfaction.
- As piling is one of the first operations on-site, pile design information is often incomplete or provided late. Piles may be constructed ‘just-in-time’ using up-to-the-minute information provided by the client or designer. Such information may be provided verbally or via a revised paper-based pile schedule leading to many revisions of the same schedule on the site.
- The construction site is not a suitable environment for bulky paper documentation. This is particularly true in the piling industry where heavy plant and large volumes of excavated soil can result in difficult site conditions, especially during the winter months.
- Active involvement in the piling works of the personnel responsible for data capture can mean that information gathering and data recording duties are secondary to completing the pile on schedule. It can be argued that this is exacerbated by the use of bonus schemes, which are used to encourage the piling gang to maintain and exceed the program of works.
- As the current process of data collection is manual, no verification is carried out on the information collected. Therefore any errors made by gang A are transferred to gang B.
- The current method of data collection does not lend itself to effective re-use of the data. Little or no analysis of process or production activities is undertaken from the data collected.

Challenges to be met in replacing the current paper-based system are:

- The number of rigs operating on any site can change during the construction works requiring each rig to be issued with a working schedule on a regular basis.

- Rig breakdowns may result in incomplete piles being finished by other gangs, therefore all previously recorded data must be made available to all working gangs.
- Although ground investigations are carried out on all sites, the nature of the work dictates that unforeseen ground conditions may be present. In such cases there may be a need to quickly respond by changing the sequence of work or increasing resources.

Analysis of the current working practices indicates that there is not only a requirement to physically replace paperwork with a robust electronic alternative but also to promote better quality construction through reduced defects. Accurate monitoring of the work in hand, the ability to share data between working gangs and to respond to the dynamic nature of the construction site is also essential. This paper addresses both the current problems and challenges by describing the application of mobile computers utilising real-time data capture over a Wireless Local Area Network (WLAN).

2 MOBILE COMPUTING IN CONSTRUCTION

Mobile computers have found popularity in many working environments and the benefits of using such devices within construction have been well documented (Baldwin et al., 1994; Fayek et al., 1998 ; McCullough, 1997) as being:

- Once only data capture at source.
- Increasing efficiency of data capture.
- Improving access to data.
- Improving data integrity.

Previous research on text-only data capture solutions has followed the development of computer hardware. Fayek et al. (1998) implemented laptops to collect site information such as labour, plant and material costs, which could then be transferred back to the head office using a modem link. Elzarka and Bell (1997) developed a touch-screen notebook computer to record condition survey data. Whilst several researchers (Songer and Rojas, 1996; McCullough, 1997; Navarette, 1999; Cox et al., 2002) have concentrated on the use of personal digital assistants (PDA's) for site data collection and information access tasks. The emergence of multi-media technologies in the mid 1990's allowed devices to be connected that could be used simultaneously to capture sounds and images, thereby enhancing text-only data capture. Two distinct approaches have been made in this area.

1. Liu, (1997) and Thorpe, et al., (1995) developed wearable systems that utilised the body to carry off-the-shelf components. The wearable solution was devised because of the impracticality of using many devices simultaneously and the unwieldy nature of their connections.
2. Alexander (1997) developed a bespoke integrated solution providing all the functionality of multi-media in a single hand-held unit. This was based on previous research by Alexander (1996) in which the requirements of construction supervisors were assessed as being, no keyboard, a lightweight unit small enough to carry and durable hardware with screens readable in near darkness or sunlight.

Research into site data capture technologies has provided a good insight into the types of hardware and applications suitable for the construction site, with guidance by

McCullough, (1993) on considerations for implementing mobile computers in construction still valid:

- Decide whether existing forms should be mimicked.
- The solution must not require additional effort over that of an existing paper-based solution.
- The hardware should be rugged to withstand the harsh environment.

However, much of this research has concentrated on standalone applications operated by knowledge workers undertaking inspection and reporting tasks, with limited application by the use of the general workforce. Where the transfer of data has been examined this has been restricted to the use of modems (Magdic et al., 2002) communicating utilising WWW protocols or via line of sight data transfer such as infrared technology (Thorpe et al., 1995). The need to provide real-time data capture for construction workers on site is still a relatively unexploited area.

3 COMMUNICATION ON THE CONSTRUCTION SITE

The idea of applying Wireless Local Area Network (WLAN) technology to the construction site is not new. WLAN technology was identified by de la Garza and Howitt (1998) as a viable solution to the problem of real-time data capture on construction sites, citing the main advantages as being no service provider charge and higher data transfer rates than other technologies. The potential for utilising the same wireless technology for both voice and data communication was also identified. However, this research identified the following potential difficulties with the technology:

- The need to reconfigure the system to suit the changing site environment.
- On-going maintenance cost for someone to manage the network.
- Relatively small coverage area.
- Interference from other WLAN users and conventional household items using the same frequency such as microwave ovens.
- Low data rate 500kbps making it unsuitable for video transmission.
- Lack of security, allowing easy access to the network by computer hackers.

As would be expected, the data rate specified by de la Garza and Howitt has now increased to 11Mbps, which would now satisfy the collection of most data types including voice and video. Interference from other single channel equipment such as baby monitors or microwave ovens using the same frequency is still a potential problem but interference from multiple WLAN's operating in the same area has been overcome. The inherent insecurity of WLAN's however, still remains a problem, Knight (2002). De la Garza and Howitt also suggested that any wireless application that is being considered should have the following two components:

1. The application needs to be time critical; and
2. The application cannot be carried out using hardwired means.

The Mobile Integrated Communications in Construction (MICC) project, (MICC, 1998) supported by the European Commission, investigated the use of an integrated communications framework to provide voice and data communication to all workers on

a construction site. The research was mainly based on Digital Enhanced Cordless Technology (DECT) which proved successful for voice communication but limited for data communication due to the lack of available hardware. Both the MICC project and de la Garza's work identified the site office as a suitable location for a centrally located site database to which all users stored their data.

The COSMOS project (Construction Site Mobile Operations Support), (Baxeavanaki et al., 2001) proposed a communication infrastructure to link the construction site to the company's head office through the use of internet technologies. The research used both DECT and IEEE 802.11b, 2.4GHz WLAN technology to provide mobile data support within the construction site, with a 5.2 GHz HiperLAN backbone for longer distances (up to 1km). Unlike the MICC project and the research of de la Garza and Howitt, the COSMOS project focussed on accessing a central data store located at the company's head office, which was achieved through the use of a satellite link. Whilst DECT and 802.11b WLAN were used successfully for data communication, the limited range of 50-200m suggest that only a single fixed location base station was used to cover the site. This is reinforced with the results from the trials, which identify the existence of moving metallic obstacles such as large vehicles as a challenge for the design of wireless networks.

Previous research in this area has concentrated on the use of DECT technology for the creation of WLAN's within construction. However, DECT has since found greatest application in the cordless telephone market with limited success within data communication. This could be attributed to the to the increased presence of IEEE 802.11b WLAN equipment, which now has a significant installed base and a superior data transfer rate of 11Mbps compared to the 552 kbps of DECT.

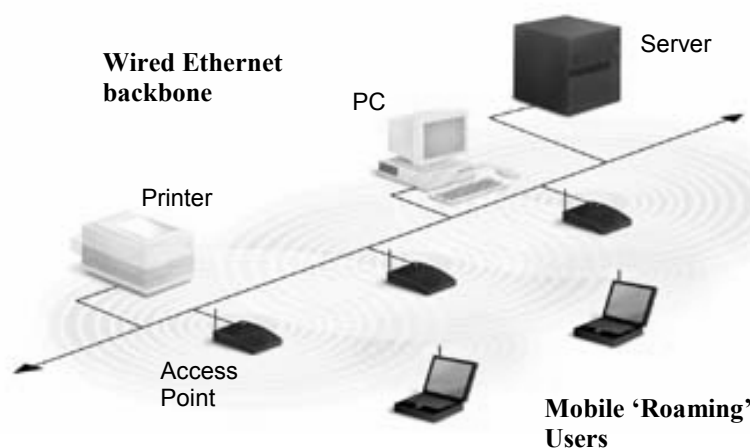


Figure 1. Typical WLAN configuration showing wired Ethernet 'backbone'

4 IEEE 802.11B WLAN

In 1992 the IEEE established a universal standard for wireless communication of computer devices. The IEEE 802.11b wireless communication protocol operates on the freely available 2.4GHz frequency internationally reserved for industrial, scientific and medical applications. This protocol is becoming increasingly popular for creating wireless networking solutions within offices, universities and hospitals to allow free roaming access to corporate, educational and medical networks. With the current delay in 3G technology for mobile communications, IEEE 802.11b is now being used to provide public WLAN services in locations such as hotels, airports and restaurants (CICA, 2002). Its ease of installation and lower cabling cost coupled with the increased number of suppliers and IT companies providing support identifies it as an attractive technology to apply on the construction site.

4.1 TYPICAL WLAN CONFIGURATION

A typical WLAN is based on Ethernet technology and comprises of a series of access points connected to a 'wired backbone' (Figure 1). These access points contain radio transmitters and receivers, and control communication in the network via antennas. Wireless bridges can be used where two networks are required to be connected together, or where a network needs to be expanded over a larger distance. In either case, such systems traditionally require some form of network cabling such as Cat 5 to connect access points and bridges to computer servers. Each access point is required to be powered and this is usually achieved using 'in-line' power through the Cat 5 cabling. To connect to the network, each computer is equipped with a wireless network card that communicates via the access points. When roaming an area covered by a series of access points, users are seamlessly transferred to the nearest point without losing connectivity. Previous research such as COSMOS and MICC projects have mimicked this structure, utilising a single 'wired' access point or bridge to provide coverage to a specific area of the site, resulting in an inflexible solution. To provide WLAN coverage to a construction site, the following inter-related factors must be considered:

4.1.1 Antenna gain

Antennas do not add any power to the signal but re-direct the energy received from the transmitting device such as an access point or bridge. By re-directing this energy, the antenna has the effect of providing more energy in a particular direction but less in others. Antennas are rated in comparison to a theoretical isotropic antenna, which has a uniform three-dimensional radiation pattern. The power of each antenna is compared against the theoretical isotropic antenna using a dBi (decibel isotropic) rating. An isotropic antenna is said to have a power rating or gain of 0dB when compared to itself, therefore, the larger the dBi rating the more concentrated the radiation pattern is likely to be. An alternative method of rating antennas is to use a dipole antenna. Dipole antennas are real antennas and have a different radiation pattern compared to isotropic antennas with a 360° pattern in the horizontal plane and 75° pattern in the vertical plane (assuming the antenna is vertical). Because the pattern is more concentrated than the theoretical isotropic antenna, dipole antennas have a rating of 2.14dBi, however when compared to itself a dipole antenna has a rating of 0dBd (decibel dipole).

4.1.2 Antenna types

The area of coverage or radiation pattern provided by an antenna is measured in both the azimuth (horizontal plane, assuming antenna is vertical) and elevation. Common antennae types are:

- Directional antennas – provide a narrow azimuth and elevation, typically 12° for high-powered transmission between two fixed points. Because the radiation pattern is more concentrated they have a higher gain, typically 13dBi to 21dBi and are typically used to transfer signals across large distances up to 10's of kilometres (depending on power of transmitter). However, they are not suitable for providing roaming access to a WLAN.
- Omni-directional antennas – provide a 360° azimuth to allow roaming access, with a variation in elevation between 7° and 60° depending on type. Due to their 360° azimuth they have a low gain, typically 2.2dBi to 5.2dBi. These antennas are ideal when centrally located as this restricts leakage of signal beyond the required area.
- Patch antennas – typically provide a 75° azimuth and 60° elevation, with a gain of 6dBi. Typically wall mounted, they concentrate the signal in the required area thereby restricting leakage but allowing roaming.

Due to the variance in azimuth and elevation, the type and positioning of antennas selected for use on the construction site is critical to ensure that sufficient coverage is provided to all users. Such considerations are particularly critical where workers may be operating at different heights.

4.1.3 Antenna cabling

Coaxial cabling is used to transfer the signal between the access point and antenna and is subject to losses. Attenuation is the loss of power through the cable, measured in dB/100ft losses increase with frequency and cable length but can be restricted by using a low loss cable. Alternatively a high loss cable may be used in a deliberate attempt to reduce the power to a specified level. Typical attenuation ratings for commonly used cables at a frequency of 3GHz are as follows:

- | | |
|---|---------------|
| • RG58 / URM76 (standard coaxial cable) | 37.5 dB/100ft |
| • RG214 / URM67 (low loss cable) | 18 dB/100ft |

The flexibility of the cable must also be considered in conjunction with the positioning of the antenna. Generally, the higher the flexibility the greater the loss in the cable.

4.1.4 Power rating

Radio frequency signals are subject to losses and gains as they pass through equipment such as access points, bridges, cabling and antenna. The power of a signal is measured using a logarithmic decibel scale used to denote the ratio of one power to another:

- $dB = 10 \log_{10} (\text{Power A} / \text{Power B})$

An increase of 3dB indicates a doubling (2x) of power and an increase of 6dB indicates a quadrupling (4x) of power. Conversely, a decrease of 3dB is a halving of the power and 6dB a quarter of the power. The transmission power and receive sensitivity of WLAN equipment is specified in terms of dBm (decibel milliwatts), where 0dBm is

equal to 1mW; 3dBm is equal to 2mW; 6dBm is equal to 4mW; 20dBm is equal to 100mW.

4.1.5 Network speed settings

Although the maximum data transfer speed of the WLAN is 11Mbps, this can be adjusted to suit different applications depending on the amount and type of data being transferred over the network. The speed of the WLAN can be adjusted in incremental steps of 11Mbps, 5.5Mbps, 2.25Mbps and 1.125Mbps. This directly affects the range of the network, with a lower speed setting resulting in a greater wireless distance, but restricting the speed at which data can be transferred. The speed of bridges, access points and WLAN client cards can be set independently, this provides good flexibility in cases where higher priority may be required for video streaming or voice data.

4.1.6 Maximum permitted power

The European Telecommunication Standardisation Institute (ETSI) has developed standards that have been adopted by many European countries for the maximum power output for WLAN equipment. The level of measurement is the Effective Isotropic Radiated Power (EIRP) which has been set at 20dBm. This level is the maximum permitted combined power of the transmitting device, antenna and cable losses. Within North America the FCC regulations specify a maximum transmitter power of 30dBm with an antenna gain of 6dBi resulting in a maximum EIRP of 36dBm. However depending on the system configuration the following rules apply:

1. For Point-to-Multipoint systems the maximum EIRP is 36dBm, however, for every 1dB reduction in transmitter power the power of the antenna may be increased by 1dB.
2. For Point-to-Point systems using directional antennas, for every dB that the transmitter is reduced below 30dBm the antenna gain can be increased from the initial 6dBi by 3Db (29dB transmitter can be used with 9dB antenna, 28dB transmitter can be used with 12dB antenna).

4.2 APPLICATION TO CONSTRUCTION

Whilst the use of a WLAN with a ‘wired backbone’ is sufficient for permanent applications it does not lend itself to the dynamic nature of the construction site. Whilst previous research has identified the potential for WLAN in construction site, there still exists a number of challenging issues with respect to its implementation, these are:

1. *Portability* - achieving a portable system that can be easily reconfigured.
2. *Scalability* - the size and duration of construction projects can vary enormously. Therefore any networking solution should be able to be easily scaled both up and down to suit the site.
3. *Cabling* - the use of network cabling is not a suitable solution for the construction site due to its fragile nature. Cabling would severely restrict the ability to easily alter the structure of the network to reflect working practices and changes in site topography; it would also require installation and maintenance on all sites, thereby increasing costs.
4. *Maintenance* - the number and location of sites on which the company work at any one time can vary enormously. Therefore, the need for a low maintenance, easily installed network is essential.

5. *Power* – many construction sites do not have access to mains power and thus rely on generated power. To provide generated power to each access point would require the installation of a power cable or a small generator to each access point or bridge. This would be costly, require the use of an electrician and severely restrict the flexibility of the network. A self-contained low-maintenance power solution is therefore required.

5 THE SHERPA SYSTEM

The Stent Handheld ElectRonic Piling Assistant (SHERPA) has been developed to provide a viable real-time data capture solution for the workforce and comprises three main components (see Figure 2):

1. WLAN infrastructure to provide mobility to data capture and access to shared data source.
2. Server side site database to store and manage a centrally located pile schedule and provide access to incoming data for analysis and re-use.
3. Client side mobile computers for use in both the rig and on the construction site to collect data and provide users access to the WLAN.

5.1 WLAN INFRASTRUCTURE

To address the challenges identified, an alternative method of applying WLAN technology to construction has been devised. The main emphasis of the solution is to provide a portable network whilst maintaining adequate network coverage to users. In order to do this self contained Wireless Network Cells (WNC) have been developed (Figure 3).

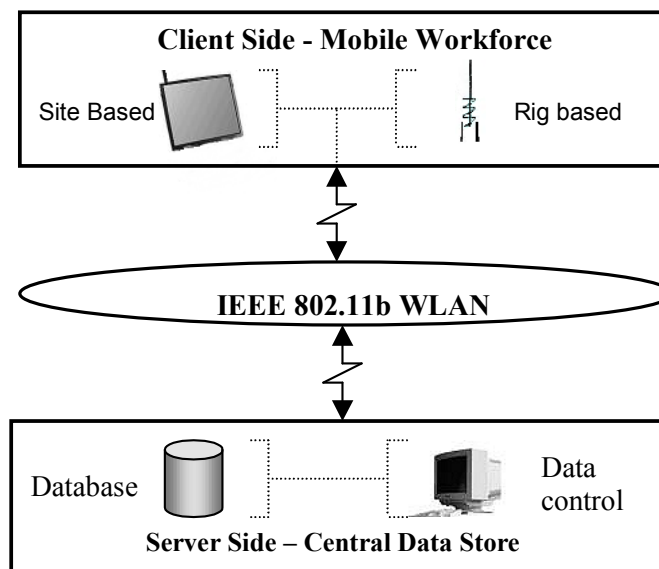


Figure 2. Main Components of SHERPA System

5.1.2 Wireless Network Cells

Each WNC provides wireless coverage to an area and also has the ability to relay data to other WNC's allowing distanced users to communicate with the site office database.

The number of WNC's through which one packet of data can pass is dependent on the speed setting of the network, as each data hop between WNC's reduces the data transfer speed by half. This happens because each WNC is required to both listen for and transmit data with half of the available speed used for each process. It is therefore essential that this restriction, together with the speed settings of each network component such as bridges, access points and WLAN client cards are assessed in the design and set-up of each WLAN.

Assuming a maximum data transfer rate of 11Mb/s and to ensure that an adequate level of service is provided, the maximum number of WNC's through which a data packet should be allowed to pass is three.

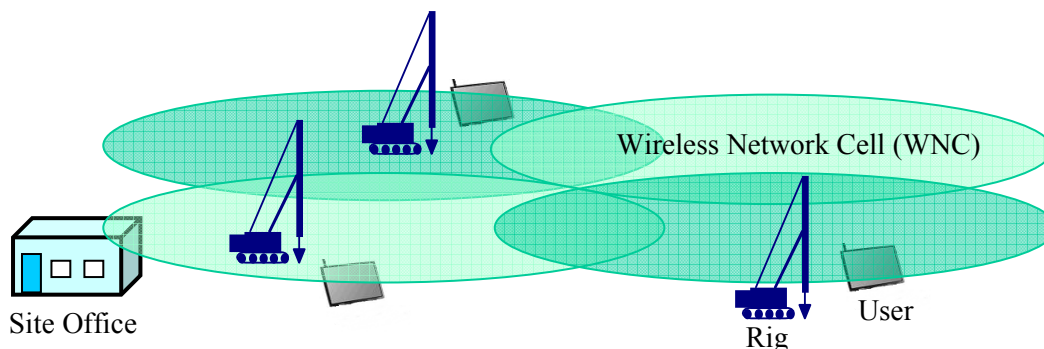


Figure 3. Wireless network cells provide wireless coverage to site

5.1.1 WNC Construction

The WNC's have been designed with emphasis on scalability and portability (see Figure 4). Each WNC comprises the following components:

1. An IP66 rated metal enclosure containing:
 - a) WLAN bridge (Cisco Aironet 350).
 - b) Rechargeable 12Ah, 12vdc sealed lead acid battery.
 - c) power converter 12vdc to 42vdc (RJ45).
 - d) Lightning arrestor.
 - e) Electronic timer switch.
2. Aluminium Telescopic Mast with:
 - a) 5.2 dBi Omni-directional antenna with 50° elevation, 3ft RG58 /URM 76 Cable;
 - b) Solar panel, battery saver
 - c) 10ft RG58 /URM76 coaxial cable;

The configuration of the bridge, antenna and introduced cable losses generate an EIRP of 17.7dBm, which is within the maximum of 20dBm permitted by ETSI.

5.1.2 Power requirements

The input power requirements for the WLAN bridge are 24vdc to 60vdc 'in-line' power via an RJ45 Ethernet cable connection. The manufacturer has used this arrangement because the unit has been primarily designed to be powered from an Ethernet 'backbone'. To overcome this, power is provided by a 12vdc battery via a converter, which transforms a 12vdc input to a 42vdc RJ45 output. The bridge uses minimal current and operates at 350mA; this alone would drain the 12vdc battery within 34

hours. Therefore, in order to maintain battery life a small solar panel 35cm x 35cm is used to trickle charge the battery. A programmable 24hr timer switch is used to turn off the power supply to the bridge during the night to save battery life.

The configuration of solar panels, battery size and timer switch has been devised to maintain portability of the units, therefore the time required between recharges is dependent on factors such as the weather but at worse is expected to be no less than bi-weekly. Each WNC could easily be re-configured using a larger battery and solar panel, however, this would be in detriment to the portability of the system.

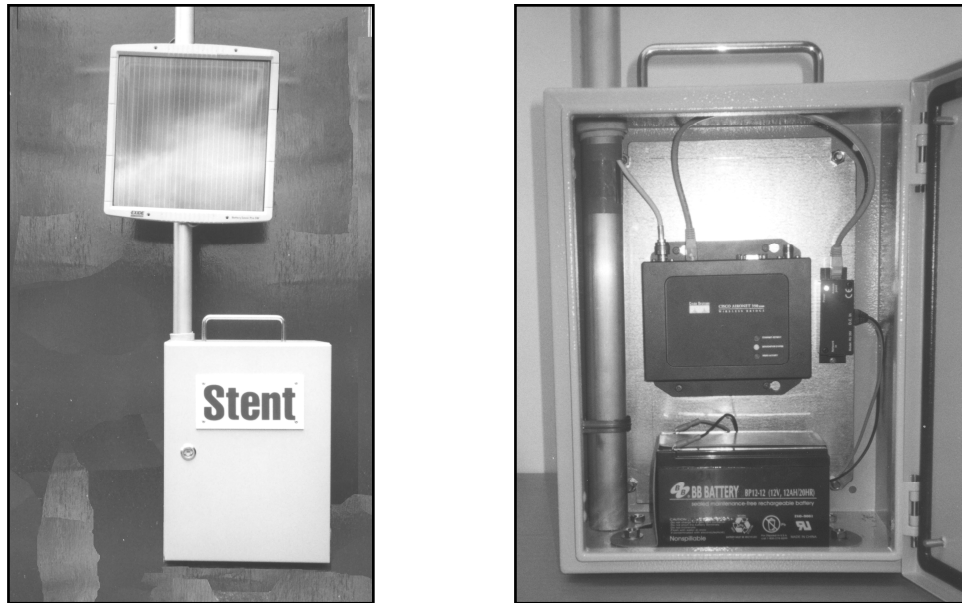


Figure 4. Mounted wireless network cell and internal layout

5.1.3 Mounting

The whole unit is designed to be fixed onto the inside of the site hoarding at a height of approximately 1.2m. An aluminium telescopic mast is attached to the enclosure with an extended height of 3.7m and a closed height of 1.3m. The Omni-directional antenna is fixed to the top of the mast and the RG58/URM76 coaxial cable passed down the inside of the mast, resulting in a watertight solution. The use of a telescopic mast allows for the antenna to be positioned at a series of heights to a maximum of 5m above ground level. This flexibility assists in obtaining the best signal when on site and to increase the portability of the unit. The mast also provides a suitable location on which to fix the solar panel.

5.1.4 WNC Coverage

Initial testing showed that each WNC would provide a coverage area of approximately 300m radius at a data rate of 11Mbps. This distance could be increased by accepting a lower data transfer rate but would restrict the number of WNC's through which a single data packet could be transferred. This suggests that the greatest distance that could reasonably be achieved between a user and the site office, passing data through the maximum of three WNC's is 1.2km, which would serve the majority of construction sites.

The problem of limited WNC hops could be overcome by using two bridges in each WNC, one listening for incoming data at 11Mb/s and the other transmitting at 11Mb/s. Although this would extend the number of hops that could be made by a single packet of data, it is likely to result in a less flexible solution. This is because two antennas would need to be co-located with the WNC, an omni-directional 'listening' antenna to allow free roaming by the workforce and another to transmit the signal. The transmitting antenna would need to have a restricted radiation pattern to limit signal confusion, thereby restricting flexibility.

5.1.5 WNC Configuration

The portable design of the WNC's allows for maximum flexibility in configuration. WNC's can be moved to serve particular areas of the site, or to avoid areas where piling has finished and the construction of superstructure has begun. The number of WNC's required for a particular site depends largely on its size but for the majority of sites it is expected to be one or two. In order to eliminate damage and regular relocating due to works, WNC's are located on the site boundary. This coupled with the use of an omni-directional antenna in this instance means that some leakage of signal outside the site boundary must be accepted.

5.2 SITE DATABASE

The SHERPA system stores all data relating to the construction of rotary bored piles in a Microsoft Access database on a desktop PC in the site office. The PC is equipped with a WLAN card to gain wireless access to the network and essentially acts as a server to all users on site. The site database is constructed in two distinct parts, these are:

1. *Pile schedule* – this stores the scheduled requirements for all piles including, required depths, construction levels, diameters, reinforcement and concrete type.
2. *Pile log* - data collected out on site is stored in a series of tables within the database with tables such as Casing, Drilling and Cage used to maintain a single record for each individual pile. Strata, Bentonite and Concrete tables contain multiple records for each pile to reflect the nature of the data being recorded.

The size of the database and number of users are not expected to exceed the limitations of Microsoft Access, which are 1Gb and 255 simultaneous users respectively.

5.2.1 Dynamic data

A number of tables are used within the database to record dynamic data and are accessed by underlying visual basic programs, triggered by actions carried out by users. One such action is the input of reinforcement cage details by the engineer. The engineer enters longitudinal and shear reinforcement bar details into the database (see Figure 5). On completion, an underlying code is used to store bar details into a dynamic array. The underlying program generates a second array calculating the volume of steel in the cage at 0.25m intervals along its length. The generated array is maintained in a dynamic cage table, which is automatically updated each time changes are made to the cage design.

5.2.2 Database management

A number of facilities are provided within the site database and can be accessed from the site office computer. These are:

Cage Designer

Cage Reference:

To Suit Pile Dia:

Cover to cage:

Shear bar lap (bar dia multiplier):

Cages

A
B
C
f

Add New Cage

Main Bars | Shear Bars

Main Reinforcement Details

No.	Diameter	Top Level	Length (m)	Bottom Level	Position
10	25	100.000	10.000	90.000	Top
12	16	91.000	12.000	79.000	Middle
20	25	91.000	10.000	81.000	Middle
25	25	72.000	10.222	61.778	Middle
30	20	72.000	12.000	60.000	Bottom
*					

NOTES

1. Top bar level to be 100.00m datum

2. All bar levels to be relative to this cage type and not associated with individual piles

Cage Length (m):

Figure 5. Reinforcement cage designer interface

1. *Pile scheduler* - this interface is provided to create and manage pile schedule and reinforcement details and is used to maintain an up to date pile schedule on the database. Each schedule is given a name and unique reference to a structure on the construction site such as a bridge abutment or retaining wall pile layout. The structure name is used by the workforce when selecting a list of piles to construct out in the field.
2. *Resource manager* - this interface is used to maintain an up-to-date list of the labourers, rigs, augers and casings used on site which are accessed by the site users in data collection drop-down lists.
3. *Pile logs* - an interface used by the engineer to view and verify individual pile logs. Each log can be viewed, printed or transferred using this interface.

5.3 MOBILE COMPUTERS

The client side application has been developed using windows based mobile touch-screen tablet computers. Computers are used by both gang A and gang B to record their respective data. The computer utilised by gang A is located within the piling rig and operated by the rig driver, this computer is used to record all information in the first two stages of pile construction. The concrete chargehand, in gang B is provided with an identical computer to record all of the remaining construction details. Providing both gangs with mobile computers maintains the flexibility of the current working method, allowing both gangs to collect and record their information independently. This also allows verification of input to be carried out at both stages, eliminating the transfer of errors between gangs.

5.3.1 Hardware considerations

The hardware requirements identified by Alexander (1996) were accepted for the development of the client side computers. However, the following additions were identified:

- *Battery life* – it is essential that the computers operate continually for a full 10hr working day without the need to replace or recharge batteries. This requirement is governed by the condition of the site which is an unsuitable place to be replacing batteries, and the need to avoid disruption to the user when operating the computer.
- *Inter-changeability* – to avoid the need for different computers within the rig and on site, and to allow greater flexibility of working, both computers were designed to be interchangeable.
- *Built in WLAN cards* – many mobile computers utilise hot-swappable WLAN cards using the PCMCIA slot. This slot is not watertight or dust proof and often results in the WLAN card protruding from the computer. It was therefore essential that the WLAN card be built into the computers and connected to a built-in flexible antenna to avoid damage.
- *Screen Size and protection* – there is increased emphasis on minimisation, and a reduction in the size of computing devices. However, for this application it is essential that the users can operate the touch-screen with their hands without requiring a wand or pen. Operatives are likely to wear gloves during work which are likely to be soiled, therefore some form of screen protection should be afforded to allow screen wiping by the user.

5.3.2 Hardware Components

Although the intention was to provide off-the shelf hardware for use on the construction site, current restrictions of mobile computers with respect to operating system, cost and size have led to the computers being specifically constructed to the following specification:

- Windows 98/2000 operating system.
- 12.1" touchscreen.
- 10Gb Hard drive.
- 128Mb RAM.
- WLAN card and antenna.
- Connections for peripheral devices such as mouse, keyboard and CD Rom/ Floppy disk, to allow programming uploading and diagnostics.

Many new mobile computers such as PDA's, notebooks and small tablets now utilise the Windows CE operating system which has been designed as a lightweight version of Windows that can be used in both industrial and mobile applications. Windows CE devices, particularly those that are robust, do not have any moving parts such as hard-drives, but instead rely on RAM and ROM to store data. This increases the portability of the unit by allowing for smaller unit sizes and maximising battery life (up to eight hours). Whilst the cost of Windows CE devices is relatively low (~£1000) and their ability to provide a long battery life is desirable, the current emphasis on smaller unit sizes currently precludes them from use in this application.

5.4 MOBILE COMPUTER SOFTWARE

The mobile computers are equipped with a Microsoft Access front-end database application containing a user interface but no data storage capability. Microsoft Access has been used in the prototype system as this is the same program as the site database, but could easily be replaced in future by a bespoke application written in Visual Basic or other language.

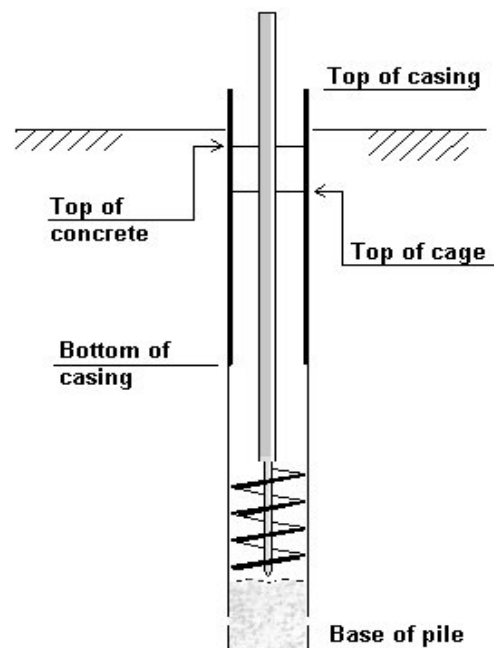


Figure 6. Rotary bored pile construction stages 1 and 2.

5.4.1 Pile Construction Phases

The software has been designed to reflect the data gathering processes undertaken on the site mimicking the following five construction phases:

1. The auger is used to pre-bore a hole to allow the insertion of a temporary casing. A temporary steel casing tube is inserted into the ground at the position of the pile to provide support to the surrounding earth and ensure that the pile is bored vertically by providing a guide to the auger.
2. The auger drills through and below the casing, removing the soil and producing an empty bore (see Figure 6). Support fluid such as bentonite or polymer may be used at this stage to provide support to unstable soils such as sands and gravel.
3. A pre-fabricated reinforcement cage is placed into the bore (the type and length of the cage must conform the scheduled requirements).
4. Ready-mixed concrete is poured into the pile to the correct level. Details relating to each pour are recorded. (Where support fluid is used concrete is delivered into the bore via a tremie pipe to ensure placement below the fluid).
5. The temporary casing is removed and the pile head is cut-off to accept a pile cap.

Information entry and verification is carried out at each stage of construction, and guidance is provided on key elements. Two forms are used on the client side machine, the pile selector form and data entry form.

5.4.1 Pile selector

This form is visible on start-up and provides the user with a convenient way to select a pile by reference to a structure on the site (Figure 7). The form presents the user with two lists; the first provides a list of all references to structures and schedules on the site database, the second a list of piles. On selection of a structure, the pile list is updated

with the available piles in the chosen schedule. On selection of a pile the user is transferred to the data input form.

5.4.2 Data Input

A single form is used as the basis to enter and view all information relating to each individual pile. After selection of the pile, the current schedule revision is transferred to the pile log tables within the database. This maintains referential integrity between the pile and the schedules within the database. Pile log information is input via a series of tabbed pages (Figure 8) that are used to reflect the data gathering processes that may be undertaken during the construction of the pile. These processes closely align with the five construction processes as follows:

1. CASING - used by the rig driver in gang A, this page is used to enter the details of the pile casing from which all further levels are recorded.
2. DRILLING – this page is used by the rig driver in gang A to record rig, auger and bored depth details.
3. STRATA LOG - an optional page used on discretion of the engineer, where changes in strata and depth may be recorded on an individual pile basis.
4. BENTONITE – an optional page used by gang B to record details of support fluid used in the pile.
5. CAGE – this page provides guidance to gang B on the reinforcement cage type to use in the pile. The gang also use this page to confirm the type and top construction level of the cage
6. CONCRETE – this page is used by gang B to measure the volume and level of concrete placed in the pile.

All data entry is made via the touch-screen utilising software keypads to enter levels, times and dates. Where deemed suitable, drop-down lists have been provided, thus minimising the need for keyboard entry.

Available Piles	
AA22	900
BB2331	900
FB334	900
D1231	1200
EF435	900
FR5341	900
G23	1200
QD3415	1200
RF3415	900

Figure 7. Mobile user pile selector using the structure as reference

Figure 8. Mobile user interface utilising tabbed pages

5.4.3 Record locking

After the entry of each page of data, users are required to lock the record. This not only prevents overwriting of the record by another user but also instils a culture of self-certification and verification within the user. Page locking is carried out by checking a box in lower right hand corner, which when activated programmatically locks all controls on the page, automatically date/time stamps the transaction with the site database and graphically shows that the record is locked (Figure 9). If the same pile record is re-opened by another user on site, they are unable to edit the record, but are presented with details of when the record was created and by whom.

5.4.4 Data validation

Data validation is performed to identify any gross errors and ensure that the pile is constructed to specification. The software has also been designed to provide guidance warnings to the user,

- the CASE page indicates whether the casing is out of tolerance.
- the DRILLING page indicates the depth required to reach the scheduled toe level.
- the CAGE page provides a breakdown of the reinforcement in the cage and the weight of the cage to be lifted.

The structural integrity of the pile is monitored utilising the CONCRETE page. This utilises the dynamic table arrays generated by the pile scheduling operation and provides the user with a theoretical concrete volume line against which to measure the volume of concrete being entered into the pile (Figure 10). As each load of concrete is poured the user enters the ticket number, delivery time, volume and top level of concrete. The details of each load are plotted in real-time against the theoretical concrete volume allowing the user to monitor under or over-break as the pile is constructed.

AA22 North Stand Schedule : Zone 1 - (Rev A) 01/06/02

Casing Drilling Strata Log Bentonite Cage Concrete

Drilling Rig S0012 Date 20/03/02 Time 11:17
Auger Ref/Dia ELA123 Dia 900 Finish 25/04/02 Time 11:47

Designed [RECORD LOCKED] [RECORD LOCKED] [RECORD LOCKED]

Casing Level (m) 4.530 Completion of dry boring 54.600
Platform Level (m) 0.000 0.000 After Addition of bentonite 0.000
Dip To Toe (m) 54.530 57.000 After bore open overnight 54.000
Toe Level (m) -50.000 -52.470 After airlifting 0.000
Drilled Depth (m) 50.000 52.470 Before concrete 57.000

Warnings Sign-off Drilling details
By Brian DEWEY
Lock Details
Locked on : 11/06/02 16:50:12

Menu
GET PILE
EXIT
Pile Ref AA22
Scheduled Details
Diameter 900
Platform 0.000
Toe -50.000
Cut-Off -1.000
Cage -2.000

Figure 9. Individual page record locking on mobile user interface

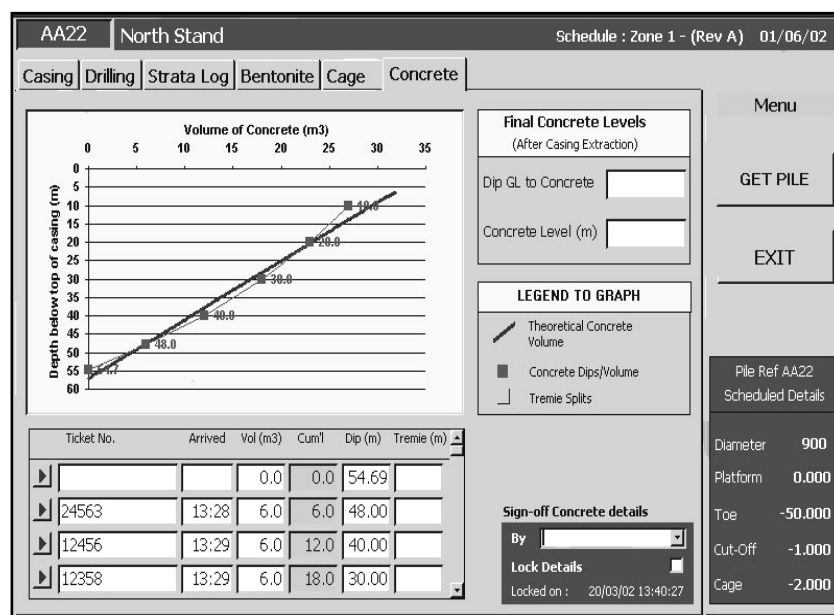


Figure 10. Real-time pile integrity graph

6 RESULTS

To date, initial testing has highlighted the viability of the system and its potential for improving communication and data capture at site level. However, in order to fully understand its effectiveness, the SHERPA system has been implemented on a yearlong project of 5000 piles, utilising four WNC's and up to twelve mobile computers. This project will be used to further investigate the use of IEEE 802.11b WLAN for real-time data capture on construction sites.

6.1 USE OF MOBILE COMPUTERS

Initial results show that the SHERPA meets the challenges of providing real-time data capture for piling works on the construction site. Early results indicate that the following benefits can be gained when using on-site mobile computers in addition to those identified by other researchers:

1. *Improve the Quality of As-Built Records.* Elimination of manual recording duties and the ability to monitor the construction of the pile below ground provides for a more accurate record of the pile construction.
2. *Improve the Quality of Construction Work.* SHERPA not only captures data but also ensure that the pile is constructed as scheduled. The elimination of on-site calculations, verbal data communication between gangs and the use of a common centrally accessed pile schedule ensures that the pile is constructed to the correct tolerances, eliminating errors in under/over boring, positioning and levels. The ability to monitor the structural integrity of the pile during construction and to spot potential non-conformances is also advantageous, something that was not previously possible.
3. *Cost Saving.* Initial results indicate that the system will save costs through avoiding re-work of insufficiently constructed piles. It is intended that this will aid in the development of a self-certification culture, relieving the client of inspection duties, and saving cost to the client.
4. *Improved quality and knowledge of workforce.* Increased understanding of the process through the use of a mobile computer will ultimately improve the quality and knowledge of the workforce. SHERPA can also be used as a training tool for new operatives to familiarise themselves with the process.

6.2 IEEE 802.11B WLAN ON CONSTRUCTION SITES

Testing of the WLAN indicates that it is a viable solution to providing a real-time data network for use in construction. The WNC's provide a fully flexible and mobile network solution that can meet the demands of the construction site such as:

- Changes in work schedules and work patterns requiring the movement of plant and machinery to different locations on the site.
- Interference from plant, machinery and other mobile communication devices.
- Changes in the site landscape, including demolition of existing structures and the construction of superstructure.

Whilst the flexibility and portability of using WNC's has been proven, to avoid difficulty with access or re-location of WNC's, it is recommended that the location and re-positioning of the WNC's be included within the program management meetings. This not only ensures that WNC relocations can be scheduled, but also maintains awareness of the WNC's and their crucial role within the SHERPA system

7 FURTHER WORK AND CONCLUSIONS

7.1 FURTHER WORK

The integration of WLAN and mobile computing provides real possibilities for further expansion of data collection and communication on the construction site. The use of

Windows platform and touch-screen computer for data collection allow for additional tools to assist the workforce on the site such as:

- Access to drawings via a CAD viewing tool to help identify piles.
- Provision of a barcode reader to automatically capture delivery ticket information.
- Access to 'on-line' manuals located on the site database computer.
- Use of a rig-based computer to undertake weekly maintenance reporting.

The installation of a WLAN infrastructure on the construction site increases potential for additional data capture and improving communications. Additions can easily be made to the site database to incorporate other data capture requirements. Whilst additional computers including PDA's or notebooks could be used on site by knowledge workers for inspection and reporting tasks, allowing all data to be stored and accessed centrally. Other communication and wireless data capture solutions that are to be tested include:

- Voice over IP (VoIP) communication using IP hand/headset, removing the need for radios on the construction site.
- Wireless video cameras for use as web cams or security, allowing flexibility of location and removing the need for hardwiring between camera and computer.
- Use of a PDA by the engineer for levelling or surveying of pile positions.
- Radio frequency location finding and mapping techniques for position guiding, vehicle and personnel movement analysis.

7.2 CONCLUSIONS

The need to provide a real-time data capture solution for the general workforce to capture piling information has been addressed by the development of SHERPA. Mobile computers are supplied to the general workforce not only as data capture devices but also to assist in the 'management' of the pile construction. Assistance is provided to the user through a touch-screen interface utilising verification of input and in-built data validation, together with below ground-level graphical representation of pile integrity. A centrally located and accessed site database is used as to store all pile construction data and maintain a single up-to-date pile schedule. This eliminates the need for paper-based pile schedules, ensuring that all piles are constructed to the most up-to-date information.

The main component of the system is the provision of a communications structure provided by IEEE 802.11b WLAN. The challenges highlighted by previous researchers in the use of this technology have been met by the development of WNC's, which provide a flexible, and scalable solution without the need for wiring. Initial testing indicates that the SHERPA system can improve the quality of information collection, pile construction and the knowledge of the workforce. The application of IEEE 802.11b technology for the creation of wireless networks within construction has been shown to be viable with potential to provide the backbone for all on-site communications.

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APPENDIX – B: PAPER 2

FULL REFERENCE

Ward, M.J, Thorpe, A., Price, A.D.F. and Wren, C. (2004). Implementation and Control of Wireless Data Capture on Construction Sites, ITcon Vol. 9, Special Issue, Mobile Computing in Construction, pp. 297-311, <http://www.itcon.org/2004/21>

ABSTRACT

A mobile site level data collection system has been implemented for piling works utilising the IEEE 802.11b wireless protocol. The system, used by dedicated ‘pile managers’ and the workforce, allows for real-time data collection and storage into a site-based server, via a mobile wireless local area network (WLAN). The use of a WLAN allows for easy access and manipulation of timely construction data to assist in the management of the project, enhancing information flow throughout the site, reducing remedial costs and improving contract performance. This paper discusses the implementation of the WLAN on two construction sites, difficulties encountered, benefits and recommendations for further work, together with user perspectives. A cost-benefit analysis also suggests a substantial saving on remedial works can be made with the introduction of site-based data capture.

1 INTRODUCTION

The implementation of mobile user data capture on the construction site requires the consideration of three elements:

- 1) hardware;
- 2) software; and
- 3) communications.

Hardware selection was recognised early by many previous researchers as an important factor in the success of implementing mobile data capture in construction. Citing factors such as screen size, outdoor readability, battery power, physical unit size and robustness as important considerations in the selection of appropriate hardware for the construction site (McCullough, 1997; Elzarka & Bell, 1997; Alexander et al, 1997) Such factors are now only currently being addressed by hardware manufacturers now keen to expand their market to include the previously neglected construction sector. However, the number of suitable mobile devices remains small. Without suitable hardware that can function reliably in the construction environment, any attempt to implement a data capture system will surely fail.

The use of appropriate software for the task of recording and accessing data is also an important factor. Although standardised packages exist for the mobile site workforce (Phair, 2000; Navarette, 1999) these are often targeted towards pre-determined inspection and reporting tasks. However, unlike manufacturing the construction site is more of a reactive environment, where unplanned changes to work regularly occur, this is no truer than in the piling industry.

Traditionally, it has been these two factors, which have formed the backbone of the success or failure of any IT solution. However, the early involvement of users in hardware selection and software development is advocated as being an important factor to successful system implementation (Ives and Olsen, 1984; Tait and Vessey, 1988). Furthermore the move towards mobile data capture requires that the third factor of communication also be considered.

1.1 MOBILE COMMUNICATIONS

Early development of mobile devices restricted the user to a limited selection of available communication technologies. The simplest form being the connection of two or more computers using hardwired means such as a docking station, serial or USB port. This was later enhanced by the introduction of infrared technology. Further developments have led to the amalgamation of mobile computing devices and mobile telecommunications protocols, with PDA's now available with integrated mobile connectivity or via a separate mobile phone, through either a wired or wireless connection such as Bluetooth. This provides the mobile user with the ability to upload and download data from anywhere that a mobile signal is provided. The currently available technologies for mobile data transfer are Circuit Switched Data (CSD), High Speed Circuit Switched Data (HSCSD), General Packet Radio Systems (GPRS) and Third Generation (3G).

CSD is the original protocol used for data transmission over Global System for Mobile Communication (GSM) mobile communications networks. Maximum transfer rates vary between 9.6kbps and 14.4kbps depending on the mobile phone handset and the service provider in use. HSCSD is essentially a high-speed implementation of GSM,

with some service providers offering a theoretical transfer rate of up to 57.6kbps. This speed makes it comparable to many fixed-line telecommunications networks and allows users to access the Internet and other data services via a GSM network. HSCSD is being rolled out across many GSM networks as a stopgap before broadband mobile services becomes more readily available. Just as with audio transmission on landline phones, both CSD and HSCSD charges are based on the time spent using the dial-up connection. GPRS is a packet switched "always on" technology supporting Internet Protocols (IP) and is typically 2 to 3 times faster than CSD with a theoretical maximum speed of up to 114kbps. Because GPRS uses the same protocols as the Internet, the networks can be seen as subsets of the Internet, with the GPRS devices as hosts, potentially with their own IP addresses. In practice, connection speeds can be significantly lower than the theoretical maximum, depending upon the amount of traffic on the network and the type of handset being used, meaning that you could get higher GPRS rates in the evening and at night. However, GPRS services should be cheaper than circuit-switched connections, with the network only being used when data is being transmitted.

3G is an emerging broadband packet switched technology currently being targeted at picture and video streaming applications on mobile handsets. Data transmission speeds are dependent upon the environment the connection is being made with speeds of up to 2Mbps (Megabits per second) achievable in indoors and stationary environments. However, for high mobility such as required in construction, these rates can be reduced to as little as 144kbps.

Established technologies such as CSD, HSCSD and GPRS allow for the transfer of data to and from mobile devices on site to remote locations such as the head-office. However, this requires data to be stored locally on the device during work, potentially placing collected data at risk if the device is damaged or, in the case of mobile devices, loose battery power and hence state. Such limitations require the user to be in active control of the data and the state of the device, increasing the complexity of the data collection task. Whilst the advent of 3G may allow true mobile thin-client capabilities for site users, issues with respect to signal coverage, speed and costs still remain.

1.2 WIRELESS COMMUNICATIONS

In order to relieve the burden of uploading, downloading and synchronisation required by other communications technologies, it is necessary to implement thin-client applications. This can be achieved through the use of currently available wireless networking technologies. Technologies such as IEEE 802.11b utilise radio waves for the transfer of data and allow connection speeds up to 11Mbps, which is far in excess of any other mobile communication technology. Whilst the indoor use of IEEE 802.11b has found popularity for replacing traditional wired LAN, the protocol is now being applied in open environments with emergence of outdoor public wireless local area networks (WLAN). Known as 'Hot-spots' these provide high speed internet access in densely populated areas such as airport lounges, railway stations and hotels to mobile corporate and private users, with analysts predicting as many as 90,000 throughout Europe by 2006 (Toland, 2002). Although still in their infancy, the possibility of providing location and context-aware services, which can be used to target advertising or services to roaming wireless users, has long been discussed (Schilit, et al 1994; Long, et al. 1996). However, due to the restricted range of IEEE 802.11b, there is a requirement to provide localised server technology to support such applications.

This technology has allowed, for the first time, users to operate functionally as a mobile thin-client without the restraints of slow dial-up connections. However, its application

within the construction environment has been little exploited. This paper discusses the implementation and operation of WLAN operating on two construction sites in London, together with the use of thin-client devices for mobile data capture.

2 BACKGROUND

A three-tier system (SHERPA) has been developed to facilitate real-time data capture for construction site piling works (Ward, et al. 2003). This consists of:

- site based server-side database;
- IEEE 802.11b wireless local area network;
- wireless thin-client devices;

The system grew out of the need to provide real-time data capture to the site workforce for the recording of pile construction information, whilst taking consideration of the construction methods, practices and the reactive nature of the site. The difficulties and requirements were highlighted as being:

- 1) the need to reduce defective work caused by incomplete, ambiguous, duplicate, missing or incorrect information;
- 2) unsuitability of the site for bulky paper documentation;
- 3) lack of verification on the data collected;
- 4) errors in data translation between the site and office;
- 5) lack of data re-use throughout the company; and
- 6) the ability to meet the reactive nature of the construction process and sequence of work.

2.1 SERVER-SIDE DATABASE

A server-side database was developed to provide a single point of access to all data relating to the construction of the piles. The intention was that this would counter the problems caused by duplicate or incomplete paper-based information on site and also eliminate the need for users to carry bulky paper documentation. The database also allows for a single point of data entry with all users having access to all of the construction data captured by other personnel. This allows for the free use of information between users and working gangs removing the burden of collating revised construction information caused by unplanned sequence changes or plant breakdowns.

2.2 WIRELESS LOCAL AREA NETWORK

It is often the case that piling works are carried out in conjunction with both demolition and reconstruction of the site, with piling undertaken in predetermined work zones. It is for this reason that a system of Wireless Network Cells (WNC) has been developed (Ward, et al. 2003) to provide wireless coverage to the site. The WNC have been designed to be fully portable, rugged and re-configurable to meet these requirements. Each WNC provides coverage to a certain area of the site allowing roaming users to connect to the server-side database. WNC can be 'daisy-chained' to increase coverage distance or divert the wireless signal around obstructions. (Fig.1)

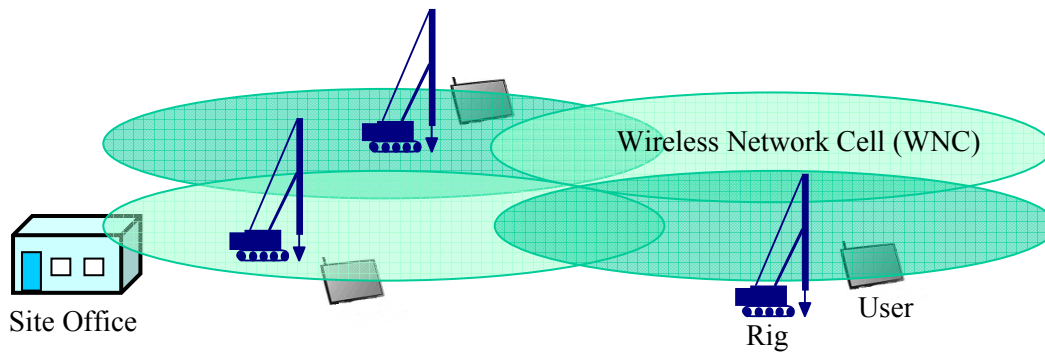


Figure 1. Typical Wireless Network Cell Configuration

2.3 THIN-CLIENT DEVICES

Each user is equipped with a touch-screen Windows CE tablet computer (Fig.2), which provides thin-client capability. This enables the user to gain access to the server-side database over the wireless network, effectively providing full desktop capability to the users. Each tablet is equipped with an IEEE 802.11b wireless card, which is fully inserted into the PCMCIA slot, leaving no exposed parts. A small retractable antenna (5cm) is provided on the tablet to improve signal performance.



Figure 2: Touch-screen tablet computer being used on site.

2.4 THE SITES

2.4.1 Kings Cross Underground Station Redevelopment

This was the first project on which the SHERPA system was deployed and is part of the development of the Kings Cross and St Pancras railway stations to facilitate the increased passenger numbers expected from the arrival of the Channel Tunnel Rail Link (CTRL) into St Pancras station. The piling works contract is valued at £10.5M and involves the construction of 575 piles with diameters ranging between 750mm and 2100mm, and depths ranging between 14m and 40m. The construction site is located to the rear of Kings Cross Station in an area of approximately 1500 square metres with the site office remotely located approximately 250m away in a site compound. (Fig. 3)

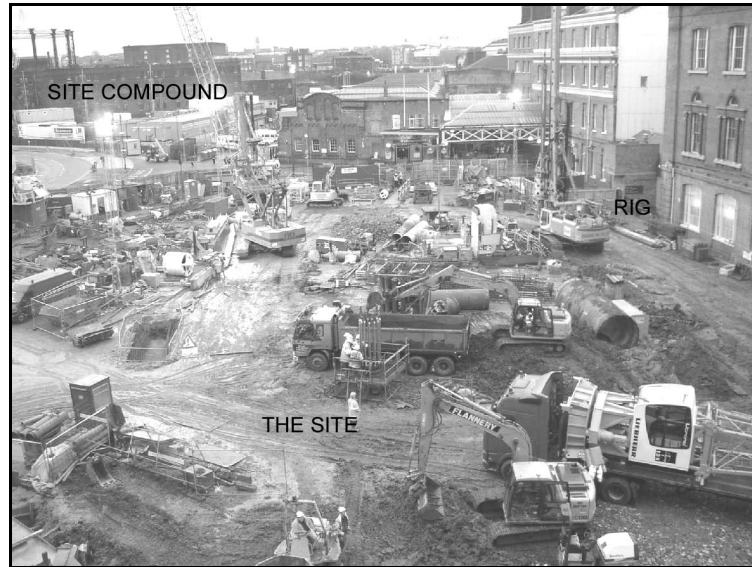


Figure 3. Kings Cross construction site showing location of site compound

2.4.2 Wembley National Stadium

The replacement of Wembley Stadium with a new 90,000 seat multi-functional sporting arena has created a single construction site of approximately two square kilometers. The value of the piling works contract is approximately £6M and requires the installation of approximately 4,500 piles ranging in diameter between 600mm and 1800mm with depths of between 20m and 40m. Due to the size of the site, the piling works contractor has been afforded an area of the site in which to locate their portable site offices and steel-fixing yard.

3 IMPLEMENTATION AND TESTING

3.1 INITIAL CONFIGURATION

Initial configuration comprised a wireless bridge located in the site office and two WNC all equipped with 360-degree omni-directional antennae. The server and tablet computers were equipped with Cisco Aironet 350 WLAN cards, although any 802.11b compatible WLAN card would have been suitable. Two WNC were initially located on the site hoarding and foreman's hut (Fig.4)

Initial tests showed that connection from site to the server was slow. This was caused by the final wireless link between the server and bridge located in the site office, creating a 'bottle-neck' to the server. This original configuration was chosen to allow for a fully flexible system, which included for moving and relocating the server as necessary. Due to the period of the contract and the static nature of the site offices, this functionality was not required and the wireless connection was replaced with a standard Tbase10 network connection between the site office bridge and the server, which considerably improved the connectivity speed.

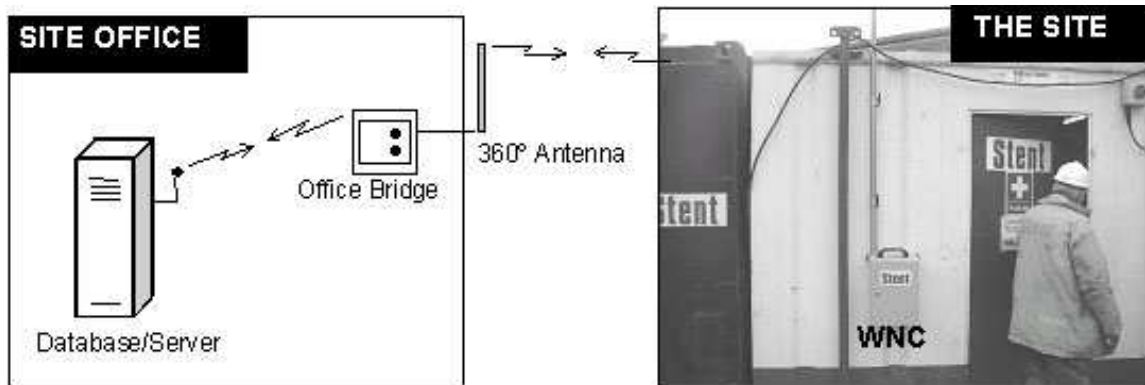


Figure 4. Initial Configuration at Kings Cross

3.2 SITE CONFIGURATION

Site offices on both sites were not moved throughout the duration of the contracts, which made it possible to maintain a fixed office bridge and server location on both sites. However, the progression of work on both sites dictated the areas in which piling could be carried out and hence how the WLAN would be configured. Piling work at both sites was carried out during both demolition and superstructure works. This meant that the dates and sequence that particular areas would be handed over to the piling works was flexible, dependent upon the completion of the demolition work. Also, on completion of piling works an area would be handed over for superstructure work with the possible creation of barriers to the signal propagation. These factors were not considered to be a difficulty to the WLAN as it had been designed specifically with this in mind.

3.3 SIGNAL PROPAGATION

Omni-directional antennas equipped with a 360-degree azimuth were initially used to propagate the wireless signal from the site office and for each WNC around the site. These antennas were selected in the original design and off-site testing of the system to allow for full flexibility in the location of the WNC and the site office.

Although located at the periphery of the site, the use of omni-directional antennas on the WNC allowed them to be easily relocated without the need for antenna re-alignment, as would be required by patch or directional antennas which provide a restricted azimuth (typically between 12 and 75 degrees). Utilising such antennas at the edge of the site inevitably causes unused signal to propagate into public or other private space. However, this was accepted as a consequence of having easier management and greater flexibility in the system.

The main difficulty for signal propagation arose from the large area of the Wembley site and the commencement of superstructure works such as shear cores. Although the signal can propagate through up to four concrete walls (dependent upon thickness), each wall reduces the strength of the signal and hence the distance that it can travel beyond each wall. The location of the shear cores and size of site meant that locating a WNC on the site boundary would not be sufficient to provide a signal in the centre of the site. Signal propagation was also hindered at both sites by the creation of hardcore spoil heaps, up to 10m high, which proved to be impenetrable to the WLAN signal. The spoil heaps were created by the demolition and earthworks contractor and as such their

positioning was out of control of the company. Varying working levels at Wembley also exacerbated the problems caused by spoil heaps and superstructure construction (Fig 5).

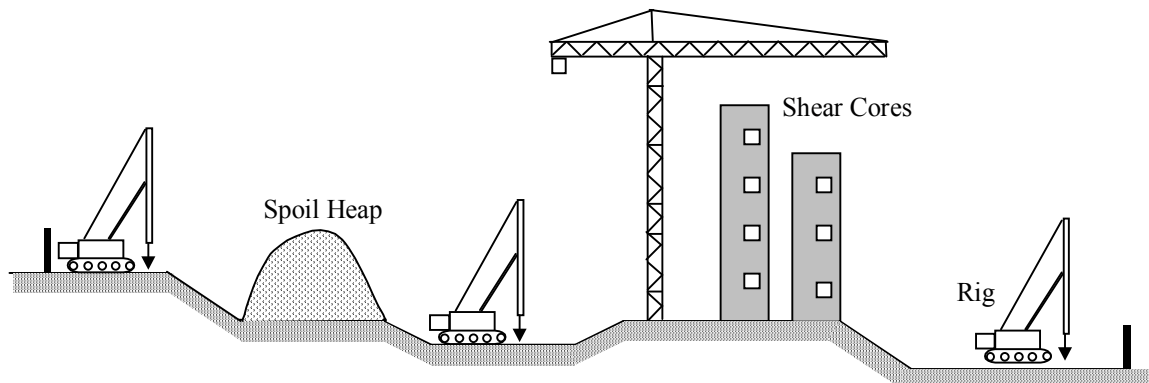


Figure 5. Typical site cross-section showing platform levels and obstructions

The layout of the site and remote nature of the site offices at Kings Cross required that the wireless signal between site office and site be passed over public and other private space. Even on sites where the site office is located on the site, the nature of wireless networks dictate that some signal leakage will propagate from the site. In such circumstances it is necessary to understand the increased security risk posed to the system, through potential hacking.

3.4 WLAN SECURITY

In order to indicate its presence to clients within its listening area, each WNC broadcasts (approximately every ten seconds) a Service Set Identifier (SSID), identifying the name of the WLAN. This enables wirelessly equipped computers within range of the access point to receive the SSID and establish a connection with the network. The 802.11b standard also includes an encryption method, wired equivalent privacy (WEP), which is based on the RC4 algorithm. Unfortunately, WEP has been cracked for over two years, resulting in a surge of publicity regarding security of WLAN's (Knight, 2002; WiFi, 2003). The cracking of WEP also spawned a movement known as 'war driving'. War driving involves driving in a car with a Global Positioning System (GPS) and wireless equipped computer or handheld device, actively seeking locations of WLAN's, both private and corporate. This practice has spawned 'war-chalkers' who chalk buildings or pavements with back-to back C's or open circles where wireless networks have been found. The locations of discovered WLAN's and corresponding SSID's are then publicised on the Internet.

Although, WEP has been cracked, there still exist a number of solutions that can be used to further secure WLAN's such as:

- Turning off the broadcast of SSID's
- Not using default settings on the WLAN equipment.
- Installing proprietary security measures such as EAP, RADIUS and firewalls.

All SHERPA wireless networks have a unique SSID, the broadcast of which is turned off. Site-office wired networks are used primarily on larger long-term contracts and often include links direct to the head-office. In such cases, it is envisaged that firewalls would be implemented between the SHERPA server and the corporate network.

3.5 WNC POWER

Each WNC was initially powered by a 26Ah sealed lead acid battery, which was designed to allow the WNC to operate for a whole week between battery swaps, thereby reducing the burden on management. However, the weight and size of the batteries (approximately 7kg) was restrictive and unwieldy, especially when being carried between the site office and WNC. A decision was made to replace the battery with a smaller 12Ah battery, which would provide enough power for two day's operation. This however, would increase the burden on the site staff to replace the batteries and maintain power to the WNC.

The use of a small solar panel to increase the operating time of the WNC through trickle charging the battery was found to be suitable only in direct sunlight when the full 350mA output could be achieved. This was reduced to a variable 100mA output in broken cloud and to 30mA in overcast or shadowy conditions proving impractical for use. Unfortunately the Kings Cross site is located directly to the north of four and five storey buildings which cast a shadow over the site throughout the day causing the output from the solar panel to be ineffective in increasing the life of the WNC.

The WNC was originally designed to be fully mobile and reconfigurable. This could only be achieved by providing a mobile power source to each unit. Users were provided with replacement batteries and recharging units and given guidance on the replacement of the batteries and the period in which they were to be replaced (every two days). However, during the first two months of operation the users often complained of a lack of signal and slow connection to the server. On investigation it was found that the WNC had lost power and the batteries had not been replaced. Although training was given, users did not fully understand the implications of failing to replace the batteries in the WNC. This is because they could still connect to the server via the office bridge when out on site, thereby bypassing any apparent need for the WNC. Although there was a lack of WNC maintenance, users were still able to connect directly to the server via the office bridge. However, because the users were operating at the boundary of the office signal they were losing speed and connectivity on a frequent basis.

4 IMPROVEMENTS

Following implementation and an initial testing period on both sites, the following improvements were made to the WLAN:

- 1) a rig mounted WNC was developed;
- 2) omni-directional antenna were replaced with a directional antenna; and
- 3) tower crane mounted WNC positions were investigated.

4.1 Rig-mounted WNC

To remove the burden of battery management on the WNC, a rig mounted WNC was developed. The intention was to design a WNC that could be fully reconfigurable but utilise the 175Ah battery located on the rig. All of the equipment from the original WNC was repackaged into a watertight and crush proof ABS case, with connections for an antenna and 12-volt power to the battery provided on the side of the case, (Fig.6). The emphasis on portability was maintained in the design of the rig-based WNC, with flat magnets placed on the underside of the unit to allow it to be relocated as necessary on the outside of the rig. The 360-degree antenna was placed on top of the driver's cab and antenna cable run down to the case. The power supply to the rig-based WNC was

taken directly from the rig battery ensuring that the signal is available even when the rig is not in-use.



Figure 6. Rig mounted WNC design and Installation

4.1.2 Directional Antenna

The use of a directional antenna in the original design of the system was avoided due to its limited azimuth, which it was thought would compromise the flexibility of the system. However, due to the distances provided between the site offices and the working site and the permanent nature of the site offices it was decided to replace the office bridge antenna with a directional yagi antenna on both sites.

The yagi antenna typically has a 30-degree azimuth, which means that the signal power is aimed in a single direction; this in conjunction with the design of the antenna increases the power and distance over which the signal can propagate (typically up to 3km at a speed of 11Mbps). Site testing showed that the yagi antenna, although deemed to be directional by the manufacturer, did in fact allow connection through 360° without difficulty.

4.1.3 Tower Crane Mounted WNC

The location of a WNC centrally in the site was not deemed necessary or thought to be practical in the original design of the system. However the following factors required such a solution to be investigated:

- large spoil heaps of hardcore;
- commencement of superstructure;
- variation in working levels; and
- size of the site.

Once the superstructure commenced it was apparent that there was a possibility to use the tower cranes as a means of providing a centrally located WNC. The tower cranes were being used to construct the shear cores and as such were ideally located to provide such coverage. Although the tower cranes are provided with power, this was via a generator. Therefore, to ensure a continuous and uninterrupted power supply, the WNC was re-designed to the same specification as the rig-based WNC but with the addition of 12Ah sealed lead acid battery. The unit and antenna were located 12m up a tower crane to provide high level signal coverage to both divert the signal around the

superstructure but also allow the signal to be passed over the spoil heaps and into lower working areas of the site, (Fig.7).



Figure 7. Tower crane mounted WNC.

Throughout the construction of the Wembley Stadium, the importance of the tower crane mounted WNC increased. This was due to the continuing construction works that led to the isolation of the piling contractors site offices and yard, which were effectively cut-off from the remainder of the site. Although this provided the required solution, the need to maintain a battery supply within the units was deemed a drawback. Especially with the core function that the tower crane WNC had in the overall system.

5 WLAN PERFORMANCE

There are many factors that can be used to measure the performance of wireless networks. In pure computing terms (Jinyang, et al. 2001), some of which are as follows:

- throughput (packets of data per second);
- losses (lost packets);
- link quality (quality of wireless link);
- signal strength; and
- delivery rates (number of successfully completed packets).

However, the nature of the research was not to determine performance in such terms but rather on the practicality and functionality of the WNC system in a construction environment.

5.1 SIGNAL PROPAGATION

The variability of radio signals can be directly attributed to the environment through which they pass, with steel having the most detrimental effect on the propagation of the signal causing it to reflect, refract and diminish in quality. The signal quality and strength were measured at static points on both construction sites using the software included with the WLAN cards.

Signal quality is a measurement of the number of data packets that have been transferred between two points on the network and is measured by an algorithm running on the wireless cards and WNC. As this represents the actual data on the network, this was deemed to be a more important value in consideration of performance, than signal

strength. On both sites, the signal quality remained relatively static in the range of 80% - 100%, with no loss of data reported.

The strength of the signal on both sites, whilst greatly improved by the changes made to the system was still highly variable, in some cases ranging between 40% and 80% at a single location within a matter of seconds. Other locations were found to have a more static signal strength, however this was also found to fluctuate around 5 to 10% over a few minutes. Whilst revisiting the same points only a day later could result in a different range of signal strengths being achieved. Such variations in signal strength were thought to be caused by the ever-changing environment and the movement of small to medium sized machinery such as dump trucks, excavators, and earthmovers.

5.2 WIRELESS NETWORK CELLS

The WNC have met their design requirements and have shown to be highly reconfigurable and suit the changing nature of the construction site especially with respect to changes in working areas. No problems have been encountered with the quality or operation of any of the units throughout the contracts, which have proved to be very stable. The use of crush and water resistant enclosures was also found to be invaluable, particularly when de-rigging, resulting in no loss over hardware over a two-year period.

5.3 WLAN MANAGEMENT

One burden of implementing WLAN in the construction environment is the requirement to provide some form of support and management to the system (Baxeavanaki, et al. 2001). One of the main factors in the design of the WNC was to enable them to be easily manageable. Where used, battery powered WNC require the use of dedicated personnel to exchange the batteries every two days. This procedure takes approximately 10-20 minutes dependent on their location. Such a requirement can be eliminated totally with the use of a rig-based WNC.

The use of a rig-based WNC also reduces the amount of management with respect to the relocation of WNC as this is effectively carried out by the rig. There is however, a requirement to manage the availability of signal to specified working areas and understand the work sequence of other contractors, both demolition and superstructure, which may affect the signal. Such management issues were more apparent at Wembley than Kings Cross, which was due to the majority of work being underground at Kings Cross during the piling works contract.

After initial set-up and following the changes made to the system after testing, the management of the signal strength and availability was performed on an ad-hoc basis at both sites. This was largely due to the flexibility in the WNC configuration, which meant that as users found problems with connection to the system, they could be resolved by the repositioning or installation of another WNC.

Basic monitoring of each WNC can be carried out at the site offices utilising software provided with the WLAN equipment. This indicates the current status of each of the WNC and whether they are active. Such limited information is all that is needed to ensure that the system is functioning as required and can take as little as five minutes twice a day.

6 THIN-CLIENT DEVICES AND SOFTWARE

6.1 WINDOWS CE TABLET COMPUTERS

Windows CE tablet computers were used on both sites as the primary hardware for data collection. These were chosen because of their relatively large screen size (800 x 600 pixels) compared to a typical PDA (240 x 320 pixels) and the need to provide touch-screen capability. Other important considerations were:

- transfective screen which could operate both indoors and outdoors;
- use of a built-in WLAN card with no protrusions;
- ability to provide thin-client capability; and
- robustness.

As each tablet computer was purchased ‘off-the-shelf’, the software for the WLAN card had to be installed onto each device separately, after which the units were ready to be used. Each unit has an IP rating of IP54 providing for limited water and dust protection and a semi-rugged construction screen with the manufacturer stating that they could survive a drop of 1m onto concrete. Whilst this rating is not the highest, the unit cost of £900 is approximately a quarter of that of a fully rugged device of the same size. To date, the tablet computers have been operating for 18 months with a low failure rate typically one every twelve months of operation. This coupled with the fact that such technology is ever-changing, suggests that semi-rugged devices may be a more cost-effective solution than fully rugged devices.

Another factor considered for their use was the requirement for the units to be operated by the site staff and the rig drivers inside the cabs. Purchasing devices with transfective screens meant that the devices could be fully interchangeable between the rig and site users as necessary

6.2 SOFTWARE AND PERSONNEL

Bespoke process orientated software was written for the capture of pile construction information (Ward, et al. 2002) utilising a Microsoft Access database. Due to the difference in contract requirements, the personnel undertaking the data capture tasks at each site were different. ‘Pile managers’ were employed to undertake all data capture at Kings Cross and were semi-experienced ‘site engineers’ with some knowledge of construction and piling. At Wembley the decision was made to utilise the site staff to undertake the data collection. This difference in personnel selection was due to the following factors:

- 1) Difference in contract requirements between Kings Cross and Wembley;
- 2) The differing nature of the piling work at each site;
- 3) Ability of the contract to support the cost of dedicated ‘Pile managers’.

The difference in personnel between sites, and their data collection tasks, required the development of different front-end programs to collect the data. The use of a specific ‘Pile Manager’ at Kings Cross meant that a single interface could be used for collecting all data relating to the construction of pile. However, the use of site staff at Wembley meant that individual process orientated front-end programs had to be created to match the work being carried out on site. Table 1 shows the difference in approach between sites, with a minimum of three personnel used at Wembley for data collection, against one at Kings Cross. This did not affect the structure of the underlying database, which

remained the same at both sites, which was due to the process-orientated approach adopted in the creation of the original system design (Ward, et al 2002).

The flexibility in the original database design provided the possibility of designing any user interface to match any particular site without affecting the underlying structure or compromising the possibility of future cross-contract analysis. However, this could prove to be a future problem if individual site managers were to request the development of individual front-end programs for each specific site or person undertaking the data collection. To provide a certain level of control it is therefore necessary to create a standard set of interfaces or profiles, which can be selected by the site or project manager at an early stage in the contract. This would enable data collection to be tailored to suit the needs of the site, the personnel undertaking the data capture and the requirements of the contract without compromising the data analysis requirements of the company.

Table 1. Personnel used for data capture at each site

Site	Process					
	Casing	Drilling	Strata Log	Bentonite	Cage	Concrete
Wembley	Rig Driver	Rig Driver	Foreman	N/A	Ganger	Ganger
Kings Cross	Pile Manager					

6.3 OPERATION

6.3.1 Battery power

Each tablet computer was equipped with a 1.8Ah Lithium-ion battery that provided approximately four hours continuous use (as stated by manufacturer). This meant that the users would need to replace the battery out on site during the day, something the manufacturer stated was catered for by providing a blinking yellow indicator when the battery required replacing, and the ability to hot-swap the batteries with the use of an internal backup battery. However, initial trials showed this not to be the case. Although the battery indicator would blink after approximately 4 hours use, hot swapping of the battery would cause the re-setting of the tablet computers to the factory setting. This effectively caused the loss of all previously installed WLAN drivers, rendering the tablets unable to re-connect to the server without being brought back into the site office and the WLAN drivers re-installed. This problem was caused by two elements:

- 1) The nature of windows CE devices, which operate wholly on memory requiring power to maintain state.
- 2) The inability of the tablet computer to swap over to backup battery when hot-swapping when the main battery is low.

In order to overcome this problem, users were provided with an on-site power point in which the tablet computers were plugged into whilst the main battery was exchanged.

To reserve battery power, users were requested to suspend the tablet devices when not in use. This had to be carried out manually as the use of the wireless card effectively meant that automated power saving operations, which suspend the device after a period of no use, did not work because the wireless card was always deemed to be active.

6.3.2 Connectivity

Users connected to the server via the Microsoft RDP protocol using terminal services. This effectively provides each tablet with thin-client desktop capability. Suspension of the tablet computer to reserve battery power effectively meant that the user could not be seen by the server, causing the server to automatically disconnect the user from their session but leaving it open for them to reconnect when they powered the machine back on. The need to disconnect and reconnect proved frustrating to the users and in some instances they were not re-connected to their old session but provided with a new session by the server. This had the effect of taking up duplicate licences and duplicating connections. This problem was managed by ensuring users disconnected from sessions before suspending the tablet computers.

Once the initial set-up and configuration of the WNC at each site was carried out, users experienced no problems with the connection between the tablet and WLAN. The design of the wireless network and changes made after testing provided for seamless connectivity between the user and the server, even when moving between WNC coverage areas.

7 USER PERSPECTIVE

Initial testing with users at Kings Cross resulted in some negative feedback relating to the system. This was caused by the initial lack of signal strength, apparent loss of signal and requirement of the user to manage the connection between the tablets and the server. However, changes made to the wireless network configuration enhanced the users perspective of the reliability of the wireless network. Although this could be due to the removal of the burden and management of the WNC by the creation of the rig-based WNC it is thought that the use of a more powerful directional antenna and increased reliability of the signal across the site is the main factor. The use of the rig-based WNC generates a signal wherever the rig is working which is often at the same location as the user undertaking the data capture.

Comparison of user perspectives between sites showed no difference in their attitude towards data collection. However, the ‘Pile managers’ at Kings Cross showed more of an interest in assisting with diagnostics when problems occurred and trying different approaches to improve the system. It is believed that this can be attributed to the role of the person undertaking the data collection. The main role of pile managers was to collect data whereas data collection at Wembley was in addition to the users operational role in the construction of the pile. This suggests that a greater level of management will be required on sites where workforce driven data capture is used rather than ‘Pile managers’.

Irrespective of the type of user undertaking the data collection, the use of wireless mobile computers on the site requires all users to undertake one or more of the following tasks during their work:

- 1) operate the data collection software;
- 2) monitor and ensure connectivity to wireless network;
- 3) connect to the server as necessary; and
- 4) ensure continuous power to the unit and hence state.

The monitoring and connectivity of the wireless network can largely be removed from users only if adequate coverage and management of the WNC is carried out before and during the contract. However, the users are still required to understand why they

may not be getting access to the server, which may be caused by loss of signal or loss of server connection. It is for this reason that training must be provided on the basics of how the wireless network operates on the site, in addition to how to operate the data collection software.

8 COST BENEFIT ANALYSIS

To determine the benefit of the system to the company, a simple cost benefit analysis was carried out for the Kings Cross contract. This took the form of comparing the cost of implementing the system against the value of the contract and cost of remedial work, caused by defects. The value of remedial work on the Kings Cross site was compared to the known value of defective work across other company sites to provide a baseline cost of defective work (Table. 2)

Table 2 indicates a 75% reduction in the cost of remedial work at Kings Cross, reducing the baseline percentage to 0.2% of contract value. Based on a company turnover of £50M this equates to a possible saving of £385,000 per annum if the system were used throughout the company.

Table 2. Cost analysis for Kings Cross Implementation

Contract Value	£10,500,000
Number of piles	575
Average Cost per Pile	£18,000
Baseline cost of remedial work (X) (0.97% of Contract Value)	£102,000
Actual cost of remedial work (Y)	£20,000
System implementation (Z)	£20,000
Saving (X-Y-Z)	£62,000

Although the use of pile managers constantly monitoring the construction, would be expected to have a beneficial impact on reducing defects, the use of a common source of data and automated auditing by the system over the WLAN as construction of the pile progresses, is believed to be the main contributory factor in the reduction of remedial work.

It is not only the cost of the system that should be considered but also the perception that such a system provides to clients and the ability to show that site level data collection can be successfully carried out. This in-turn realises the prospect of additional work being granted on the basis of having a sound system to monitor the construction of the work and an improvement in contract performance.

9 FURTHER WORK AND CONCLUSIONS

9.1 FURTHER WORK

It is inevitable that some battery powered WNC will be required on larger sites, as such it is imperative that an easier form of monitoring the WNC is developed. This could take the form of a web-based interface, which could provide information such as the input power the WNC and highlight those WNC that require imminent battery

replacements. This could be enhanced with the use of wireless low cost PDA devices being provided to staff and alerts made via the WLAN. Alternatively a GSM dial-up to alert staff by text message on their mobile phone could be used.

Keeping track of the location of the WNC on the site is also an important role, which could be assisted by providing a graphical interface of the site layout or an aerial photograph onto which the system manager could drag and drop WNC and rigs. Such a visual aid may also prove beneficial in highlighting potential problems in signal deterioration or quality from future superstructure work.

The use of the tablet computers providing a larger screen size than that of a PDA, allow for greater flexibility in design of user interface and inter-changeability between pile manager, site user and rig user. However, this comes at a cost to battery consumption. Low power consumption devices and PDA's, particularly those for mobile WLAN use are available. However, this is usually at the cost of screen size, which has a large drain on battery power. Therefore the provision of a tablet that can be operated throughout a whole day, thereby reducing the burden on the user to manage the device state is still required; alternatively investigations into the use of a PDA for limited tasks should be investigated.

The need to tailor data capture requirements for particular contracts, clients and users has been highlighted. This suggests that efforts should be made towards providing a standard set of interfaces or user profiles from which the project manager can tailor the data collection to meet such requirements at the start of the contract. However, the need to ensure a common underlying database structure throughout the company remains the priority.

Problems associated with connection to the server via the wireless network have been exacerbated by tablets which require power saving operations to be carried out. Therefore, the need to provide an alternative mechanism for the data capture should be explored. It is envisaged that a web-based data collection system could be developed based on the work already carried out. Such a system would require the user to be in control of the data transfer between the tablet and the server, may require some form of short-term data storage on the tablet but would eliminate the cause of duplicate sessions and the need to retain particular software platforms on the server. Such a web-based system would also allow for remote clients or head-office personnel to connect into the site server to monitor progress. However, it is important that security is taken account of in such a configuration.

9.2 CONCLUSIONS

The use of reconfigurable WNC to provide wireless mobile coverage for data capture on the construction site has proved successful. Although the design of the wireless network allows for reconfiguration and portability to overcome obstructions, the following factors should be considered on any implementation of site WLAN:

- spoil heaps;
- variation in platform/piling level;
- construction of superstructure;
- uncontrolled space, public private and on-site;
- size of the site.

When using WLAN on the site, it is essential that user coverage be maintained. This will reduce the burden on the user to ensure that wireless connection is available.

However, the nature of radio-based technology is such that some intermittent loss of signal has to be accepted, unless a large amount of redundancy is introduced into the system, which would in-turn increase maintenance requirements.

The use of rig-based WNC, which allow for permanent power supply from the battery on the rig has proved successful. With the rig effectively becoming the WNC, it is only necessary to maintain a signal over to each working area to ensure that users have full connectivity to the server.

The use of windows CE tablet devices has been explored and their suitability for the site verified. The ability to utilise a single device such as a tablet in many applications such as pile manager, rig and site user has been shown to be beneficial. However, the current lack of battery power requires that the mobile user be actively involved in maintaining the state of the device. Irrespective of the role in which the tablet is used, there is still a requirement for the user to connect and re-connect to the server via the terminal services interface.

The ability of site personnel to conduct data collection tasks both as a primary task and secondary task to their day-to-day work has been explored. This research indicates that those users who undertake the data collection as their main task are more likely to be pro-active in the control and improvement of the system. This suggests that sites which specifically employ 'pile managers' to undertake data collection would have a lower overhead for managing the system to those which utilise site staff in the data collection role.

A cost benefit analysis shows that the value of remedial work as a percentage of turnover has reduced from 0.97% to 0.2% with the implementation of the SHERPA system. This would equate to a possible saving of £385,000 in remedial works cost should the system be implemented throughout the company.

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APPENDIX – C: PAPER 3

FULL REFERENCE

Ward M.J., Thorpe A, Price A.D.F and Wren C. (2004). IEEE 802.11b Wireless networks: An Enabler for Real-time Data Capture in Construction. *Proc. CIB World Building Congress 2004, Toronto, Canada, 1-7 May, Paper No. 586, p.233 (11 pages)*

ABSTRACT

A mobile site data collection system has been implemented for piling works utilising a web-based database system over an 802.11b wireless local area network (WLAN). Site data collection is undertaken by the workforce and data transferred between a site-based server and users in real-time. The use of the WLAN allows for real-time access and manipulation of the data by site engineers to assist in the management of the project, enhancing communication and information flow throughout the site. The use of web-based data collection improves the accessibility of the data both within the site and for external parties such as the head office, client and supplier, with the potential to allow the contribution of site data to project collaboration tools in real-time. The implementation of real-time data capture can be attributed to a number of factors including the availability of enabling technologies, cost, complexity of project and types of data being recorded. This paper discusses the results of utilising the system on a number of real construction projects and the potential for its application to the wider construction industry. However for this to be realised, factors such as network configuration, network maintenance, software development, financing of hardware, sensitivity and standardisation of data collection all need to be addressed.

1 INTRODUCTION

The need for site based data collection is generic to all construction projects because it forms the backbone of project control, in both financial and management terms. For a contracting company it may be important to know the following information about a certain site task:

- how long the task has taken;
- problems or difficulties encountered during its execution; and
- resources used, such as materials, plant and labour.

For the project manager, such information is important to allow balancing of resources, planning further work and controlling the project. For the quantity surveyor, it is important to place a value against such information in order that the work can be properly valued, and variations assessed where necessary. For the estimator it is important to know task durations and resource levels in order to improve estimate accuracy. Whilst for the senior management, an overview of the current status of the contract may well suffice.

However, the requirements for site data go well beyond the contractors' own use. Some, or all of the data may well be required by other contract parties, such as the client, designer or supplier where it could be integrated into 4D CAD models, integrated project models, shared via a web portal or fed into project management and delivery systems.

The increasing availability and general awareness of mobile computers and mobile communications suggest that real-time integrated project management systems utilising site-collected data are attainable. This together with the increased emphasis on information dissemination and data management places electronic site data collection systems at the forefront of the drive towards better contract management and control. However, there are many obstacles to the successful and practical implementation of real-time site data collection on the construction site.

This paper discusses the use of an integrated web-based site data collection and project management system for piling, utilising an IEEE 802.11b wireless network as the backbone for communication. A method of data profiling to allow site managers to tailor data collection to contract requirements is also discussed, together with the potential for the system to be implemented throughout the wider construction industry.

2 SITE BASED DATA COLLECTION

Unlike the implementation of IT in clean, environmentally controlled environments, special consideration has to be given to how data collection systems can be implemented on the construction site taking consideration of factors such as:

- condition of the site, especially in poor weather;
- transient, multi-disciplinary and multi-cultural workforce.
- differences in site location; and
- size and complexity of the site.

Although the importance of such factors should not be overlooked, it is fundamentally important to understand hardware, software and communications requirements to arrive at a suitable solution. This is particularly true in respect of mobile computing.

2.1 HARDWARE

Many devices have been used to assist in the collection of construction site data, from PDA's (Navarette, 1999), Laptops (Fayek et al. 1998) to barcode readers (Baldwin, et.al 1994) and radio frequency identification (Jaselskis, et al. 1995). Whilst such technologies paved the way for construction site data collection, many have been stand-alone requiring specific device based programs with device-based data storage. Recent advances in PDA technology appear to have been the enabler for the collection of site data, however, these devices have been primarily targeted at knowledge workers, who due to the nature of their work, can easily integrate such devices into everyday working lives.

The application of site data collection technologies has been particularly successful in the area of inspection and reporting (Elzarka, et al. 1997; Cox, et al. 2002), where data are collected and controlled by knowledge workers. In such cases the collected data can be retained on the device for long periods, days rather than hours, before being transferred usually by hardwired or infrared means. This may be appropriate where the person responsible for the data collection is the primary user of the data, but for users on site, any such system would be secondary to completing the task in hand. Therefore, in order to allow the collected data to be used to enhance the project control it is necessary that it be transferred from the device at the earliest convenience

The requirements for successful application of mobile computing hardware on the construction site have been highlighted by many researchers in purely physical terms citing factors such as rugged, touch-screen, sunlight readable, and 'small enough to fit in pocket'. However, the integration of mobile computing with mobile communications requires that consideration be also given to the operating system, software and communication technologies in order that an appropriate and workable solution is provided.

2.2 MOBILE OPERATING SYSTEMS AND SOFTWARE

There are currently three market leaders of mobile computing operating systems, these being Palm (utilising Palm OS), Windows CE (based on Windows technology) and Symbian EPOC (originated by Psion), each offering their own interface and integrated software. For each there is also a considerable amount of third-party add-on software available through shareware, freeware or by direct purchase.

However, one factor common to all operating systems is the inability to use software across-platform without purchasing two software packages, which then may or may not be fully compatible without a third party conversion package. This forces providers of site data capture systems to initially make a choice of platform, which invariably restricts the availability of software and the selection of hardware available to support the software. When these factors are added to hardware functionality and communication requirements, the issue of how to provide site data collection systems increases in complexity.

2.3 WEB TECHNOLOGY FOR DATA CAPTURE

One main driver for the adoption of mobile computing has been the ability to connect to the Internet from anywhere, hence one common factor between operating systems is their use of web-browser technology. The possibility of utilising the web browser for site data collection potentially provides the following benefits:

1. platform independence;
2. increased number of devices to choose from;
3. allows real-time data collection;
4. limited or no on-device data storage, increasing data security;
5. easier access to data;and
6. easier integration and sharing of data through standards such as XML.

One major consideration is the difference in functionality in web-browsers between operating systems, which even with standards produced by the World Wide Web Consortium (W3C) can still prove to be a stumbling block. However, this can be largely overcome through the development of browser-aware software.

2.4 MOBILE COMMUNICATIONS

Mobile communications such as the GSM (Global System for Mobile communications) and GPRS (General Packet Radio Services) have allowed the creation of an IT efficient mobile workforce, empowered to access e-mails, work schedules and information whilst on the move. However, restrictions on bandwidth, typically 9.6Kbps for GSM and 28Kbps for GPRS, and high calling costs, limit the volume of data that can be reasonably transferred, requiring data entry to be completed off-line. Signal variability across the country and variation in available bandwidth based on the time of usage presently make this technology only suitable for uploading and downloading tasks. The advent of 3G (Third Generation) mobile communications, with an increased target bandwidth of 2 Mbps, may prove to be the enabling technology for real-time data collection on mobile devices. However, restrictions on cost and available coverage may still apply.

Whilst GSM and GPRS may be appropriate for many organisations collecting site data, it is the users who are responsible for data transfer to and from the site. This requires the user to understand the availability of signal, which could be variable or non-existent, depending on site location, which may lead to data having to be stored locally on the device or an alternative method of data transfer used. Such potential difficulties increase the burden on the site user and potentially place the effectiveness of data collection systems at risk.

In order to overcome the variability and potential complexity of current mobile telecommunications, a localised communications infrastructure utilising IEEE 802.11b has been explored which would have the following potential benefits:

- standard seamless integrated communication route for the data;
- removing responsibility for communications and data storage away from the site user;
- increase security of the data; and
- allow data integration into real-time project management systems.

3 A MOBILE IEEE 802.11B WIRELESS NETWORK

In 1992 the IEEE established a universal standard for wireless communication of computer devices. The IEEE 802.11b protocol operates on the freely available 2.4GHz frequency internationally reserved for industrial, scientific and medical applications. Whilst the protocol has gained popularity for replacing traditional wired LAN in offices, it is now being applied in other environments with the emergence of outdoor public wireless local area networks (WLAN) and ‘hotspots’ in airport lounges and motorway service stations. This protocol has also previously been tested on the construction site (Baxeavanaki, et al. 2001). However, in all instances, such wireless networks allow limited roaming capability for users (typically up to 50m from an access point) without losing connection. This restriction is a function of the network design, in that they utilise a wired backbone on which a router or server resides to provide functionality for the mobile users (Figure 1). This essentially fixes the wireless network in place and does not allow for flexibility in the re-locating the network without re-laying network cabling.

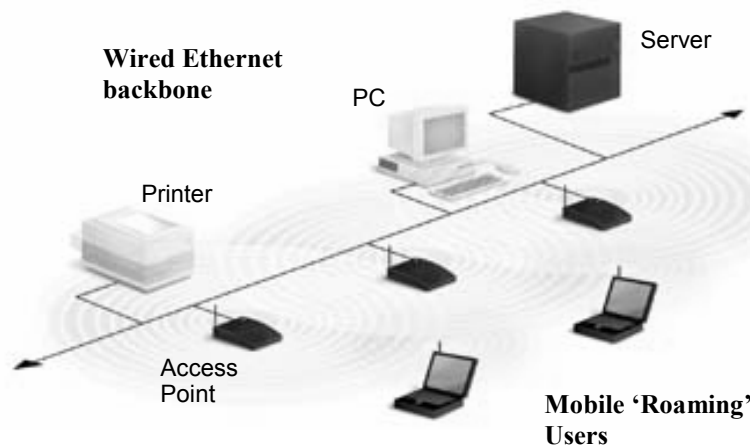


Figure 1. Wireless network with wired backbone

Such an approach would not be sufficient for effective use on the evolving construction site, where demolition, substructure and superstructure work are often carried out. These factors, together with unforeseen and unplanned movement of plant, machinery, men and materials, to facilitate changes in work program, require that any communications technology should be portable, reconfigurable and flexible to provide coverage to all working areas. It is for this reason that a system of Wireless Network Cells (WNC) has been developed, that create a fully ‘wireless’ network (Ward, et al. 2003)

3.1 WIRELESS NETWORK CELLS

The WNC has been designed to provide flexible wireless network coverage to the construction site and has been used successfully on a number of large construction projects in London, including Kings Cross and Wembley. The WNC consists of a self-contained, wireless access point enclosed within an ABS case, weighs approximately 3kg and has connections for 12-volt power supply (mains or battery) and an antenna (Figure 2). The coverage area of each WNC varies depending on the antenna used and

the obstructions around the site, but typically covers an area of approximately 20,000 square metres. Because of their small size, each WNC can be placed at varying locations around the site, but have typically been placed on advantageous high positions such as tower cranes or rigs (Figure 2). Alternatively where no advantageous point exists, portable telescopic masts have been deployed on which the WNC is mounted.

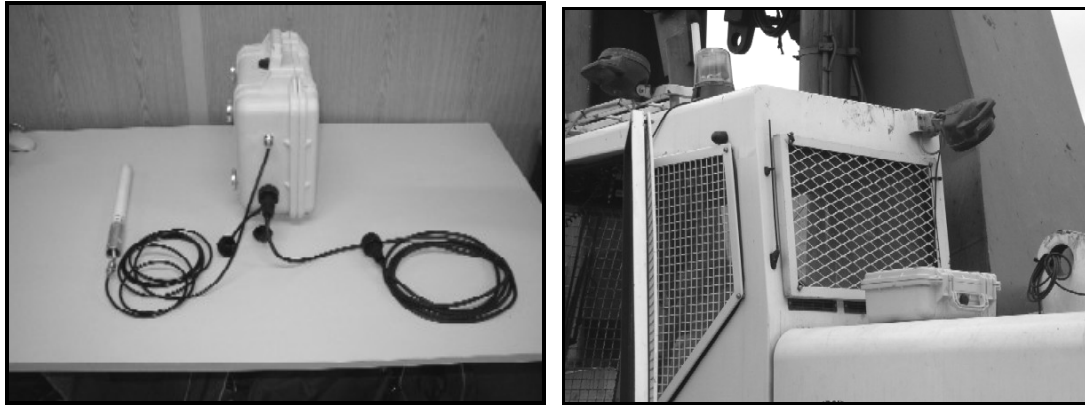


Figure 2. Design of a WNC and its Installation on a piling rig

3.2 NETWORK CONFIGURATION

The configuration of the WNC network is cellular in nature and not dissimilar to that used for mobile telecommunications. Each WNC provides localised area coverage for user connection and communicates to other WNC (Figure 3). Users are free to roam anywhere coverage is available and are seamlessly transferred between each WNC.

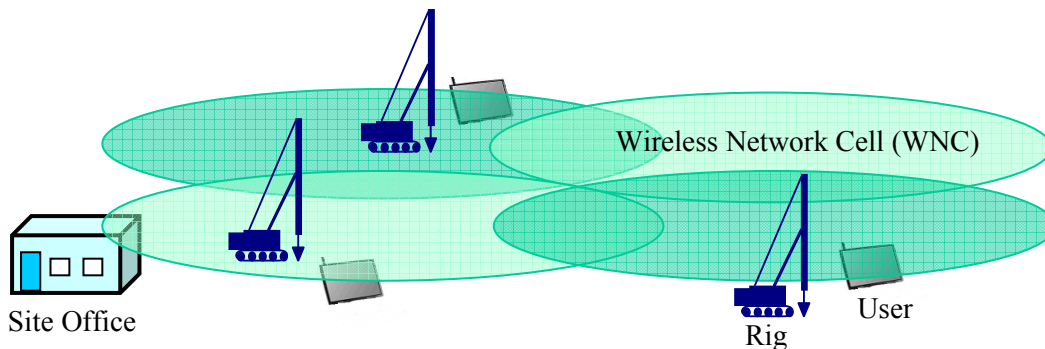


Figure 3. Cellular configuration of the WNC

3.3 RESULTS FROM WLAN IMPLEMENTATION

Experience of operating the reconfigurable wireless network on a number of construction sites indicates that the following major factors should be considered:

- spoil heaps;
- construction of superstructure; and
- uncontrolled space, public, private and on-site;

An initial major concern was the potential for signal degradation caused by structural steelwork and moving machinery and plant. However, the flexible nature of the network design allows this to be effectively managed by relocating and adding WNC where necessary. Experience on-site during construction work indicates that signal can be maintained to all staff through active monitoring of the network to ensure that coverage is maintained. The greatest proportion of maintenance time is taken in the site establishment phase where movements of vehicles and staff may not be fully managed and initial testing and adjustment of the network is required to provide best performance. The management and implementation of the WLAN can be greatly assisted by forward planning and an understanding of sequence and activities of other contractors especially with respect to the placing of spoil heaps.

4 WEB-BASED SITE DATA COLLECTION SYSTEM

A web-based site data collection system has been developed for the recording and management of rotary bored piling operations utilising the WNC as the backbone for communications.

4.1 BACKGROUND

Rotary bored piling has a number of distinct but inter-related processes, in simplistic terms these are:

1. a temporary hollow casing is installed in the top layer of soil (typically 8m) for stability;
2. the drilling rig, drills through the casing and the soil creating an empty bore;
3. a reinforcement cage is placed in the bore;
4. concrete is then poured into the bore; and
5. the temporary casing is removed.

The piling industry relies heavily on records made on the ground by the workforce during each process, who in-turn rely heavily on information provided by the engineers in order to construct the piles. Poor collection of data, caused by site conditions, missing or incomplete construction information or poor communication routes can lead to increased defective work. As a result, information received back from site at the end of the day, is missing or incomplete requiring project managers and engineers to collate as best they can inadequate records and delivery tickets to pass onto the client or internally within the company. To gain any benefit from the site data, time and effort is required by the project managers and engineers to collate and process data, a rare commodity on the construction site. Even if the effort is taken to process and collate the data, analysis is often days late and the potential for early identification of problems has been missed, potentially resulting in additional cost to the contractor. As a result the **Stent Handheld Electronic Piling Assistant SHERPA** was developed, the main objectives of the system were:

1. improve the flow of information on the site;
2. standardise data collection methods via a common shared data set;
3. allow easy re-use of the data;
4. allow better management of the project through use of collected data; and
5. reduce defective work caused by the use of poor information.

4.2 SYSTEM ARCHITECTURE

The SHERPA system is based on a standard web-server architecture. A server located in the site office is used to provide localised web-services to wireless users via the wireless network (Figure 4). All software used on the server is open-source, reducing the cost of the system, a particularly important factor in construction where low capital costs are desirable. Web-content is served via an Apache web-server and all web pages are created using PHP (hypertext pre-processor), HTML (hypertext mark-up language) and JavaScript. Server-side scripting such as database transactions and creation of dynamic web-content are carried out utilising PHP with client-side interaction such as ‘on-click’ events carried out utilising JavaScript. All data are stored in a mySQL database on the server, which is a SQL based database, allowing easy manipulation of data and transfer to other systems via the standard SQL language if required

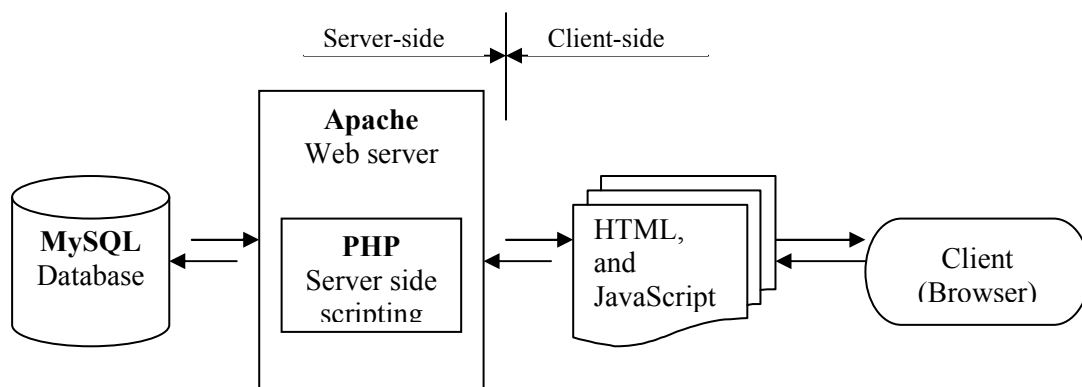


Figure 4. Architecture of the SHERPA system

4.3 SOFTWARE DEVELOPMENT

A Microsoft Access based system was used for rapid prototyping of the system and tested at both Kings Cross and Wembley. This consisted of a single database with a two-tier interface, one for on site data collection the other for data management and project control. All data was stored on the server, and site users were equipped with touch-screen Windows CE tablet computers (Figure 5). All access to the server was via Microsoft Terminal Services, essentially creating a truly thin-client application. However, the following differences in the sites, dictated that a number of interfaces be developed for the data collection:

- complexity of data collection required for each specific contract;
- the type and role of personnel carrying out the data collection; and
- requirements of the client.

At Kings Cross, a single interface combining a series of tabbed process-oriented data collection pages was designed for the site data collection (Ward, et al. 2002) and was completed by specifically employed ‘pile managers’ and site engineers. At Wembley, however, site staff were used requiring a different set of interfaces to be created to match each site process. This increased the complexity of the system, as each user log-on would need to be targeted to their required interface. Although managed effectively, this approach lacked flexibility both for Wembley and possible future sites where

changes in data collection requirements or site personnel roles during the contract may lead to further interfaces being required.



Figure 5. Touch-screen tablet computer operated by site personnel

4.4 DATA PROFILES AND ACCESS

To overcome the difficulties of managing and creating multiple interfaces for specific contracts, a system of data profiling was developed, utilising the ability of the web architecture to generate dynamic content. A standard set of process orientated web-based data collection pages were created for both ‘detailed’ and ‘simplified’ data collection allowing the choice of two levels of data collection for each process (Figure 6).

Data profiles are created by selecting one or a number of data pages from either the detailed or simplified page set, which can then be applied to a specific user login. This allows site managers to dictate what data collection they require on each site, how access is managed, who has what access, and how complex the data collection should be for each individual process, thereby eliminating the need for many user interfaces to be created and managed for specific contracts. When a user logs on their profile is obtained from the database and a set of buttons dynamically created which provide access to each page contained in their profile.

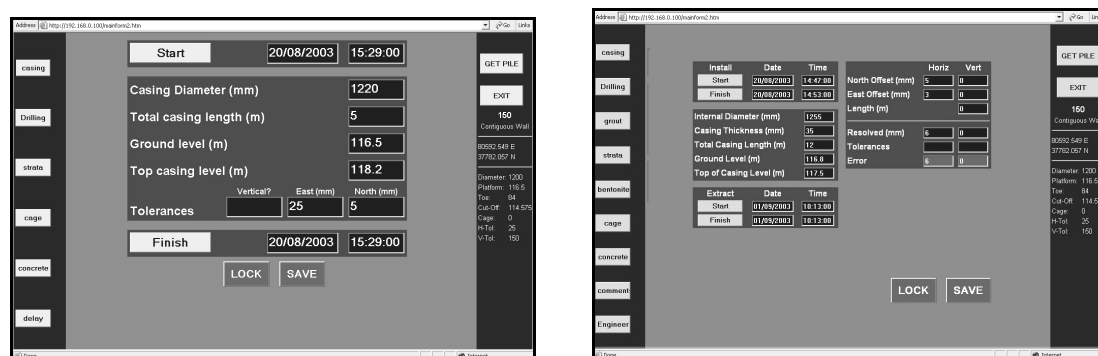


Figure 6. Comparison of Simplified and Complex data Collection Pages

4.5 DATA MANAGEMENT

A series of ‘manager’ pages have been created for the management and analysis of design and site data. These pages are designed to assist with the collation and collection of site data and to improve the management of the project through the following tasks:

1. creation of standard pile schedules from which all piles are constructed;
2. management of plant and personnel on the site
3. management of concrete delivery tickets and concrete cube testing;
4. analysis of site productivity
5. simple cost analysis based on work completed to date, (i.e. materials, labour and plant used); and
6. production of standard pile log reports,

In addition to these tasks, the web-based format has allowed expansion of the management system to include ‘site view’ pages utilising functions such as 2D ‘click’ maps to generate a plan view of the site with a pile layout. These use pile schedules and site collected data to provide an interactive, simplified graphical representation of the site which can be potentially used for planning work and viewing the current status of the project.

All data management pages are provided with an on-line manual, by clicking a single button on each page. This eliminates the need for a paper-based manual, reduces immediate support and encourages a process of self-learning. As with data profiles, management profiles can be created which allow dynamic content to be served to users based on their login, allowing specific access to individual portions of the management system based on the profile. This is ideal for external access, where the client may need access to pile reports and site viewer, the senior management may want to utilise the site viewer, whilst the cost clerk at the head office may want access to materials delivery information.

5 RESULTS

The SHERPA system has been successfully deployed for the management of rotary bored piling works on a major shopping and leisure development in London. Initial results indicate an improvement over the original MS Access based system in the following areas:

- improved access to information via the web;
- improved management of information; and
- the ability to tailor data collection to site requirements.

Site users has indicated the following benefits in the utilisation of web-based data collection over that of the MS Access system:

- a simpler log-on procedure; and
- improved communications between device and server.

The perceived improvement of communication can be related to the fact that unlike the use of Terminal Services, the web-based system only requires users to be connected to the network when exchanging data with the server. Although this does not reflect a truly thin-client application, the benefit to the user is that they only need to be in an area of

coverage when returning or requesting data from the server. This enables the use of the system in areas where the signal may not propagate, such as in deep excavations, manholes or other covered areas. An added benefit is the reduced traffic on the network as users are not required to be permanently connected. Although this arrangement increases the risk of data loss from individual pages, the use of process orientated data collection means that the amount of data transferred with each page is minimal.

6 APPLICATION TO WIDER INDUSTRY

The use of the IEEE 802.11b wireless network protocol embedded within the WNC provides a flexible and portable local communications infrastructure, which can be expanded or reconfigured as necessary to suit the evolving site throughout the construction phase.

Although SHERPA is a specific web-based database system developed for the management and collection of piling information, its use has shown the potential for utilising the protocol for the collection and dissemination of site data in real-time. Whilst the SHERPA model could be applied to individual trades on the site, the greatest potential benefit would be gained from utilising such a system for the majority, if not all, the site contractors. However, there are a number of fundamental issues, which would affect how such a system could be fully utilised throughout the construction phase of the project.

6.1 CONFIGURATION

The model discussed in this paper has been applied to a single contractor with tailored application development. Therefore, two alternative models are proposed for the expansion of the system throughout the construction site (Figure 7).

Model 1 uses a shared WLAN with each individual contractor maintaining control of their own data via a server located in their site office. This allows effective sharing of the wireless network and individualised off-site control but segregates the data, restricting the potential for on-site collaboration. This also increases the complexity of data transfer as each individual contractor would be responsible for transferring specific data to clients, project models and suppliers, limiting the potential for real-time collaborative working. Model 2 shows a single site data collection server for all contractors, which can be accessed by all parties to the contract. The utilisation of data profiling would allow contractors to maintain their own database on the server; alternatively, a single combined project database could be used. In either case, this model increases the potential for sharing of data and the contribution of this data to collaborative technologies in real-time. However, issues of security, access and data ownership sensitivity would need to be addressed.

6.2 MAINTENANCE

Due to the changing site environment, both proposed models would require some form of management and control of the wireless network. Model 1 would require each contractor to be responsible for individual hardware and software such as servers, however, Model 2 would only require the contractor to provide and maintain software.

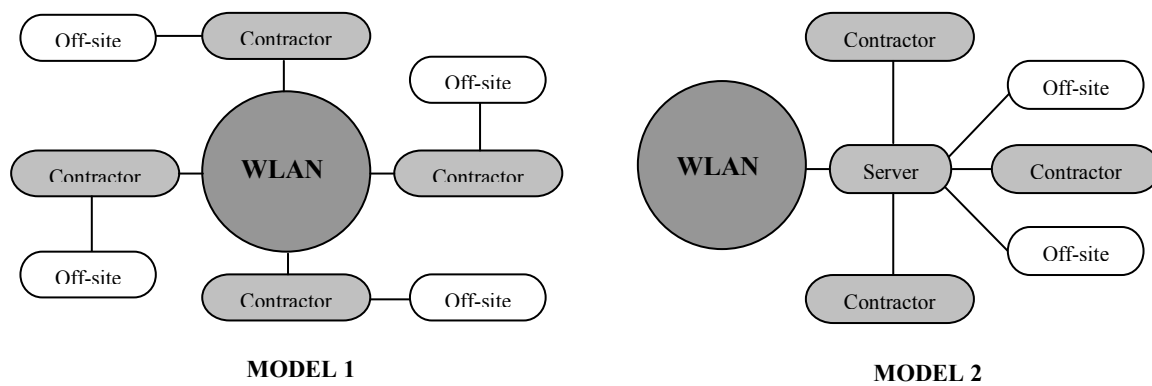


Figure 7. Proposed models for integration of web-based data collection on site

6.3 FINANCING OF HARDWARE

The cost of implementing the WLAN would vary depending on the size and nature of the construction site. Table 1 shows an example of WLAN costs for both Kings Cross and Wembley for the piling works.

Table 1. WLAN Cost Implications for Kings Cross and Wembley

Contract	Duration (Wks)	Size (m ²)	WNC Qty	Cost (£)	Maintenance (£)	Total (£)
Kings Cross Station	40	1,500	4	4,800	2,500	7,300
Wembley Stadium Redevelopment	42	400,000	15	18,000	12,000	30,000

The cost of WLAN for both sites is based on actual purchase cost against the contract and does not include any depreciation or additional value gained from further implementation of hardware on future sites. Although a single technician was used to manage the WLAN, train site staff and troubleshoot hardware and software for data capture on the piling works, the maintenance cost shown in table 1 is indicative of the amount of time required to maintain the WLAN only.

For collaborative working, the potential benefits may encourage the cost of the network to be shared amongst several contractors on the same site. The cost could be distributed taking into account the contract structure and individual contractor use. In all cases, it is likely that contractors would try to recover the costs of such a system on a contract-by-contract basis, where ultimately the costs would be borne by the client. Model 2 would reduce hardware costs for contractors' as they would be able to share a common server, whereas Model 1 would require the purchase of a server for each contractor on each site the system was operational.

It is envisaged that the selection and financing of mobile computers and other data collection hardware would be made by individual contractors depending on factors such as when, where and by whom the data capture is to be carried out. The utilisation of the IEEE 802.11b protocol and web-based data collection software, improves the selection of hardware, which may otherwise be restricted by available software and operating systems.

The fragmented nature of construction means that getting the smaller contractors' or sub-contractors' to buy into such a system may prove difficult. In order to achieve this, assistance from main or lead contractors may be needed to drive the system further down the chain.

6.4 SOFTWARE DEVELOPMENT

Although off-the-shelf construction related software exists for use on mobile devices for tasks such as work scheduling, timesheet completion, asset management and building surveys, it is likely that software for site data collection would be tailored to meet contractor specific tasks, depending on how the data were to be used. The use of web-based data collection, whilst requiring specific programming skills, would allow for such data to be easily integrated into the company and shared between other parties.

6.5 STANDARDISED DATA COLLECTION

The individual nature of companies, how they work and their data needs often affect what data are to be collected on site. Such data may include details of plant, labour and materials and be enhanced with detailed production data such as dates, times and durations. This leads to companies creating bespoke software applications or individualising off-the-shelf packages to meet such requirements. Whilst such a requirement should not be overlooked, for data to be in a re-usable format there is a need to standardise data sets for transfer throughout construction, such as through the utilisation of Industry Foundation Classes.

7 CONCLUSIONS

The use of the wireless network cell (WNC) incorporating the IEEE 802.11b protocol allows for the provision of a localised computer network on the construction site to facilitate real-time data collection. A web-based data capture system has been implemented, allowing users to access and contribute data to a project database in real-time through the use of mobile computers equipped with web-browser software.

This system has shown to be successful in the control and management of piling works, enhancing the flow of information between site activities and the site office and improving site communications and project control. The use of web technology increases the accessibility of the data to other parties to the contract such as the client and supplier, enhancing the flow of data and knowledge of project status to all, whilst providing the potential for real-time contribution of site data to project models and collaborative technologies.

The potential for its application to the wider industry has been explored and two models suggested for its wider application on the construction site. However, wider issues such as system costs, data ownership, system maintenance, standardised data sets and software applications need to be addressed.

8 ACKNOWLEDGEMENTS

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APPENDIX – D: PAPER 4

REFERENCE

Ward, M.J, Thorpe, A., Price, A.D.F. and Wren, C. (2004). Delivering Web-based Project Management Support to Construction Site Workers.
(Submitted to Automation in Construction, June 2004)

ABSTRACT

Web-based project management systems (WPMS) have found popularity within construction and have shown to be beneficial in improving communications and document transfer between project participants. However, the integration of construction site workers into such systems is a relatively unexplored area. This paper presents the development and implementation of a web-based data capture and management system for piling works, utilising a site-based web server and wireless network. The system effectively allows for the expansion of existing WPMS to include construction site workers, whilst improving the management and understanding of the project in terms of quality, cost and progress.

1 INTRODUCTION

Many examples of web-based technologies aimed at improving communication, collaboration and information exchange between project participants, can be found within the construction industry, these include:

- web-enabled project management systems;
- company extranets and intranets;
- performance monitoring systems [5];
- design management extensions [2,22];
- supply-chain integration; and
- e-commerce.

Such systems use a variety of tools and technologies such as e-mail, document management, CAD and digital cameras. They facilitate the sharing of data by different parties at all stages of the construction lifecycle from design to final inspection.

The most extensive use of web-based systems within construction involve web-enabled project management systems (WPMS), [6,8,11,20]. WPMS incorporate a variety of tools and technologies, using the communication capabilities of the web to store, share, manipulate and control project information and documentation. They have been shown to provide a number of benefits [1,13,21] beyond those of improved communication, these include:

- the elimination of paper-based reports, reducing printing, posting and storage costs;
- a reduction in site visits through the use of up-to-date digital photographs or web-cams;
- a reduction in delays from awaiting late or missing information;
- the avoidance of mistakes from the use of out-of-date information; and
- more accurate information transfer between project participants.

The bulk of communication between construction project participants resides at the middle manager level of the business [13]. As such, the structure of WPMS have been designed around the communication requirements of workers residing at this level, relying heavily on the collation and contribution of project data from *knowledge workers*. However, at the construction site level, there still remains a considerable lack of integration of WPMS beyond that of accessing and contributing documents such as requests for information (RFI), work schedules, drawings and project plans, a task again undertaken by *knowledge workers* such as site engineers.

Research into the use of web-based technologies on the construction site [14,17] has highlighted the potential for the integration of site data into WPMS. The most prominent of these being the use of digital images, which have been shown to be most effective in improving resource planning and control, rapid problem solving and generating visual as-built records.

The provision of ‘final mile’ computing to the construction site worker has been addressed by many researchers [7,12,15,16] and several influencing factors have been identified, such as:

- harsh site conditions;

- perceived lack of suitable hardware for the site;
- reluctance of companies to provide IT on the construction site;
- perceived inability of workforce to utilise computers;
- perceived lack of appropriate communications protocols; and
- cost of system development and implementation.

Whilst factors such as harsh site conditions, cost and company reluctance may still remain barriers to effective implementation of workforce driven systems, developments in rugged hardware and wireless communications technologies [24] create the potential for the integration of construction site workers into WPMS. This coupled with a willingness of construction workers to utilise mobile computing technology on the construction site [4], suggests that the ‘final mile’ is now an achievable aim.

A key factor in the success of any construction company is the delivery of individual projects. Assuming that the estimating process is accurate, it is the performance of site activities and project management that dictate if the project is profitable or not. Efficient and effective site-based data collection is critical to the success of all construction projects as it forms the backbone of project financial and management control. High quality site-based data capture also increases estimating accuracy. Although arguments still exist regarding the validity of comparisons made between manufacturing and construction [9], site data within construction can be considered to be the equivalent of production data within manufacturing. However, whilst manufacturing relies heavily on production data to improve business and process performance, the re-use of site data within construction remains relatively small.

This paper presents the development and implementation of a wireless web-based site data capture system (SHERPA) within Stent Foundations Limited (SFL), a major UK piling contractor. Operated by the site workforce for the management and construction of piling works, SHERPA utilises a three-tier system comprising a web-server, wireless site network and wireless touch-screen tablet computers to extend the WPMS to the construction site workforce. The results demonstrate that web-based technologies can be used successfully on the construction site and allow for data collected by the construction site worker to be integrated into WPMS with the added potential for real-time communication of data.

2 THE SHERPA SYSTEM

The SHERPA system was borne out of the requirement to improve the quality and understanding of the progress of piling works through the implementation of electronic data capture on the construction site [24]. Following analysis of existing site practices, a number of key issues were highlighted suggesting the use of a server-based central data repository and data capture system, these being:

- multiple revisions of paper-based documents on the site;
- data transfer and inscription errors made by the site workforce;
- just-in-time design data being delivered to the site;
- real-time data sharing requirements between different working gangs; and
- lack of data verification at the point of delivery.

A detailed description of the SHERPA system follows, with particular emphasis on the interfaces provided for data capture, manipulation and management together with the contribution of such data to WPMS.

2.1 SYSTEM ARCHITECTURE

The SHERPA system is based on standard web-server architecture (see Fig. 1). Web-content is served via an Apache web-server and all web pages are created using PHP (hypertext pre-processor), HTML (hypertext mark-up language) and JavaScript. Server-side scripting such as database transactions and creation of dynamic web-content are provided by PHP with client-side interaction such as ‘on-click’ events carried out using JavaScript. All data are stored in a Standard Query Language (SQL) based database (MySQL) on the server, allowing easy manipulation of data and transfer to other databases if required.

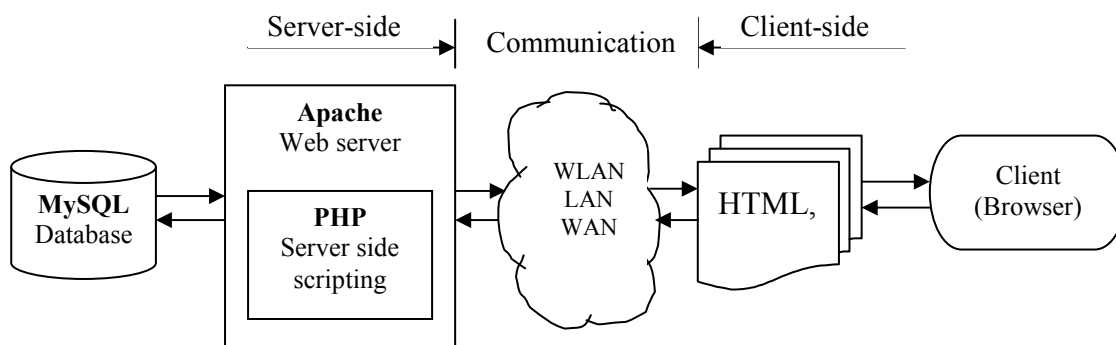


Figure 1. Architecture of the SHERPA system

All software used on the SHERPA system is open-source, reducing the cost of the system. A particularly important factor in construction where low capital costs are desirable and where localised server support may be required on a number of sites simultaneously

A number of communication protocols have been utilised within the SHERPA system. Site-based clients such as construction workers access the server via a specially designed site Wireless Local Area Network (WLAN). However, the communication method used by on-site and remote *knowledge workers* can vary depending on a number of key factors, these being:

- the number of *knowledge workers* on the site;
- the value, location and duration of the contract; and
- the availability of external communication protocols.

Access to SHERPA for site-based *knowledge workers* can be gained through the site WLAN or by the creation of a LAN in the site office, the main factors affecting the choice of protocol being the duration of the contract and the number of *knowledge workers* on the site. The communication protocol for remote *knowledge workers* is dependent on the inter-relationship of contract duration, location and availability of communications.

The SHERPA system has been structured to provide two distinct services: site data capture and data management. The site data capture service has been designed for the site operatives to monitor and record the construction details of each pile utilising a

single design data source located on the site server. The data management service offers *knowledge workers* both on site and remote from the site, the ability to generate reports, manage and visualise site data.

2.2 SITE DATA CAPTURE SERVICE

The site data capture service has been designed specifically for the construction worker operating on the site but may be used by a variety of personnel. The service utilises set of process-orientated data capture pages to disseminate and gather data at the point of production, with each page related to a specific piling sub-process as follows:

- *Casing installation*: used to accurately measure properties and the position of the temporary casing against specified tolerances.
- *Drilling*: used to monitor and record the depth of the pile to ensure that the design toe level is achieved together with recording auger properties, drilling rig, driver and foreman.
- *Strata measurement*: used to record excavated strata details and depths to enable a soil profile log to be created for each pile
- *Support fluid*: used to record the integrity of support fluid against a set of specified tolerances such as PH, sand content and viscosity.
- *Cage installation*: to guide users on the correct cage for the pile, monitor the type of cage used and assist with the accurate positioning of the cage within the pile bore
- *Concrete tickets*: to record all concrete delivery details, including batch and delivery times, add site concrete test results such as slump tests and record the cubes for off-site testing.
- *Pile Concreting*: to register the volume and concrete loads placed in individual piles and to monitor the structural integrity of the pile.
- *Delays*: to record the type and duration of all delays occurring during piling works on the site using a standard set of delay criteria and drop-down boxes.
- *Final positioning*: to record the final position and level of the pile against design details.

The service offers two levels of data capture for each identified sub-process: simple and detailed. It adopts a method of data profiling to generate dynamic interfaces for site-data capture personnel. Data profiling was developed following the implementation of earlier static interfaces [24], which identified the requirement for a flexible data capture interface based on the following factors:

- the type of personnel undertaking the data capture;
- different task assignments for site personnel between contracts depending on the personnel available and site hierarchy created;
- the type of piling being carried out on site may dictate a greater level of control and monitoring of the process, such as piles constructed under support fluid; and
- the specification for recording of the piling works may be different depending on the client and the sensitivity of the contract.

Data profiles are created by selecting one or a number of data pages from either the detailed or simplified page set, which can then be applied to a specific user login (see Fig. 2).

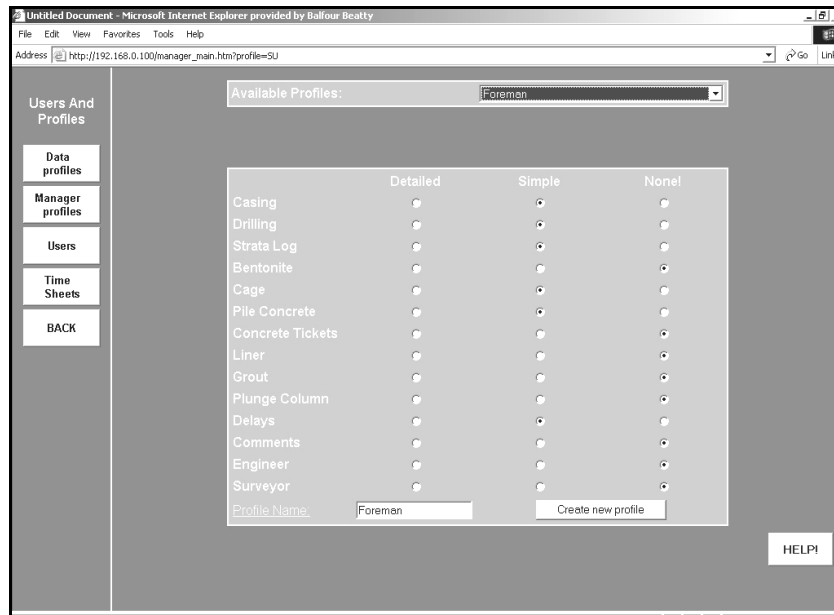


Figure 2. Webpage for the creation of data capture profiles

The method of data profiling allows site managers to dictate what data collection they require on each site, how access is managed, who has what access and how complex the data collection should be for each individual process.

2.2.1 Data capture interface

The site data capture interface is divided into three distinct parts: navigation bar; menu bar; and data entry section (see Fig. 3).

Located on the right hand side of the screen, the navigation bar allows users access to the pile selector from which they can request the latest pile design details from the server for the current pile. Once a pile is requested the design details and construction tolerances are embedded within the navigation bar allowing them to be accessed by all data capture pages for data verification purposes and to be viewed by the user as required.

The menu bar is located on the left-hand side of the screen and includes a set of dynamically generated buttons, each button relating to either a detailed or simplified data capture page depending on the data capture profile of the user. On pressing a button, the relevant data capture page will become visible in the centre of the screen. The saving of the data for each individual page is controlled by the site user. An alert message is thus used to confirm that the user has saved the data from the current page prior to changing pages.

The centre of the screen is reserved for data entry and verification. Each data page has been designed for touch-screen operation and includes embedded JavaScript to alert users to possible non-conformances and assist with page navigation. Users enter data by clicking on the relevant cell corresponding to the data entry to be made and entering data into the pop-up box that appears (see Fig. 4). Pop-up boxes for date, time and number entry are embedded within each page together with pop-up select lists generated from standard contract details or concrete deliveries. An underlying continuous self-auditing process checks data entries, alerts users to possible non-conformances, and

provides guidance on pile design requirements such as toe depth, cage position, levels and concrete volumes

Figure 3. Simplified drilling page provided by the data capture service

2.2.2 Management of concrete deliveries

Pile construction comprises two main materials: concrete and reinforcement. Concrete expenditure within SFL equates to approximately 30% of company turnover, therefore the volume and quality of concrete used within the piles plays an important role in both assessing the structural integrity of the pile and for financial reporting within the company. Prior to the implementation of SHERPA the rationalisation of concrete deliveries with pile construction and positioning was hindered by common factors typically associated with the use of paper-based documentation on the site, such as:

- incomplete or missing data;
- lost concrete delivery tickets;
- incorrect transcription of ticket details; and
- reconciliation of cube results with concrete loads and pile locations.

To overcome this, a concrete ticket management system was introduced within SHERPA. Each concrete load arriving on the site is subjected to site testing and the creation of cubes for off-site compression strength tests, work that is carried out by a concrete technician prior to the load being placed into any pile. Within SHERPA, the concrete technician is provided with a touch-screen tablet computer for recording all of the concrete ticket details using the concrete tickets page provided by the data capture service.

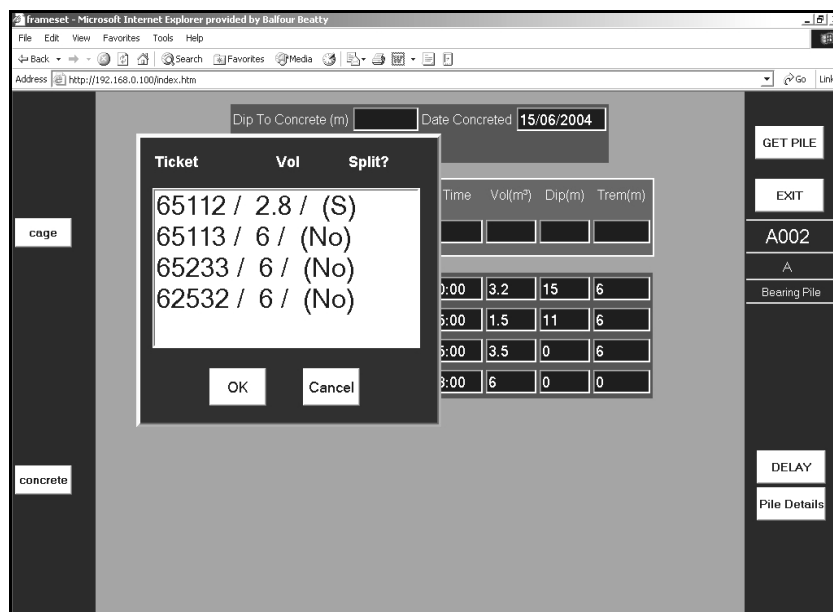


Figure 4. Concrete ticket entry page utilising pop-up box of available tickets

The placement of concrete into the pile is governed by the concrete ganger, with each pile requiring a number of loads or part loads to achieve the final level. In order to assist with the correct assignment of concrete loads to piles, SHERPA dynamically produces a pop-up list of any unused full and part-loads for the concrete ganger. Once the delivery truck arrives at the pile head, the concrete ganger requests the ticket number from the truck driver and selects the relevant ticket from the list of available loads (see Fig. 4). On assigning the load to the pile, the ganger is requested to confirm the volume placed into the pile. If only part of the load is used, SHERPA calculates the remaining volume and retains this on the pop-up list as a split load for further assignment. This method not only improves the integrity of data, but also removes the burden of the site concrete ganger having to re-enter ticket details for every pile to which the load is assigned. In addition, any problems caused by inadequate compression strength results can be easily reconciled to one or a number of piles, without reference to unorganised paper-based documentation.

2.3 DATA MANAGEMENT SERVICE

The data management service allows site *knowledge workers* and remote *knowledge workers* to access, maintain, manipulate and view pile design and construction data stored in the database. The service has been sub-divided into a number of sections, access to which is governed by the use of management profiles. Similar in functionality to data profiles, management profiles are created and administered by the project manager and once created can be assigned to specific user logins for both on and off-site access.

The interface of the data management service has two sections: the menu bar and the main screen (see Fig. 6). The menu bar is located on the left-hand side of the screen and includes a set of buttons providing access to data management sections. Similar to the data capture service, each menu bar is dynamically produced based on the current users management profile and has been designed to maintain a level of consistency for users who migrate between both services. The main screen is multifunctional and allows for

data entry, management, reporting and visualisation. All sections of the data management service are outlined in the following subsections.

2.3.1 Contract settings

Contract settings provide an interface for the management of static data sets such as, concrete mix types, piling rigs, augers and expected site soil types, many of which are used on pop-up boxes integrated within the data capture service. In addition, contract specification and tolerance details such as horizontal and vertical pile position, support fluid, maximum allowable slump and reinforcement cage position are maintained within this section.

2.3.2 Design schedule management

One of the fundamental reasons for the design and development of the SHERPA system was the creation of a formalised and structured data source of pile design details, which could be accessed from the construction site during piling works. Emphasis has thus been placed on effective management and importing of pile design schedules. Due to the high number of possible design revisions a single database table ‘pile details’ has been created to store one set of design details for each pile (see Fig. 5). A second table ‘schedule’ is used to record pile schedule details such as date, revision and work section, allowing the creation of a one-to-many relationship between schedules and pile details. When a schedule is imported, all details are automatically transferred to the schedule table and each individual pile design detail either imported, overwritten or discarded, depending on the existence and completion status of the pile, ensuring design details for completed piles remain unchanged.

Due to the number of pile details being imported in one schedule (up to 500) there is a requirement for a quick and easy method for the identification of major data errors or missing values in the imported data. This has been achieved through the development of a visualisation service for rapid checking of imported data using a histogram representation of critical design elements such as pile length, toe level, cut-off-level and cage level (see Fig. 6). Each line of the histogram represents one pile, with the length representing the data value to be checked. On discovering a possible erroneous value, both the pile reference and value can be obtained by floating the mouse over the relevant histogram line

2.3.3 Users and profile management

The users and profile management section allows the entry and management of user details and the creation of data capture and data management profiles which can then be assigned to specific user logons.

ID	FileRef	Sched...	Dia	ToeLevel	CutOffLevel	CageLevel	Platform	CastingL...
1	101	1	1200	79.500	114.275	115.150	116.500	114.275
2	102	1	1200	88.000	114.275	115.150	116.500	114.275
3	103	1	1200	79.500	114.275	115.150	116.500	114.275
4	104	1	1200	88.000	114.275	115.150	116.500	114.275
5	105	1	1200	79.500	114.275	115.150	116.500	114.275
6	106	1	1200	88.000	114.275	115.150	116.500	114.275
7	107	1	1200	79.500	114.275	115.150	116.500	114.275
8	108	1	1200	88.000	114.275	115.150	116.500	114.275
9	109	1	1200	79.500	114.275	115.150	116.500	114.275
10	110	1	1200	88.000	114.275	115.150	116.500	114.275
11	111	1	1200	79.500	114.275	115.150	116.500	114.275
12	112	1	1200	88.000	114.275	115.150	116.500	114.275
13	113	1	1200	79.500	114.275	115.150	116.500	114.275
14	114	1	1200	88.000	114.275	115.150	116.500	114.275
15	115	1	1200	79.500	114.275	115.150	116.500	114.275
16	116	1	1200	88.000	114.275	115.150	116.500	114.275
17	117	1	1200	79.500	114.275	115.150	116.500	114.275
18	118	1	1200	88.000	114.275	115.150	116.500	114.275
19	119	1	1200	79.500	114.275	115.150	116.500	114.275
20	120	1	1200	88.000	114.275	115.150	116.500	114.275
21	121	1	1200	79.500	114.275	115.150	116.500	114.275
22	122	1	1200	88.000	114.275	115.150	116.500	114.275
23	123	1	1200	79.500	114.275	115.150	116.500	114.275
24	124	1	1200	79.500	113.925	114.800	116.500	113.925
25	125	1	1200	79.500	113.925	114.800	116.500	113.925
26	126	1	1200	79.500	113.925	114.800	116.500	113.925
27	127	1	1200	79.500	113.925	114.800	116.500	113.925
28	128	1	1200	79.500	113.925	114.800	116.500	113.925
29	129	1	1200	79.500	113.925	114.800	116.500	113.925
30	130	1	1200	79.500	113.925	114.800	116.500	113.925
31	131	1	1200	79.500	113.925	114.800	116.500	113.925
32	132	1	1200	79.500	113.925	114.800	116.500	113.925

Figure 5. The 'pile details' table structure and data within MySQL

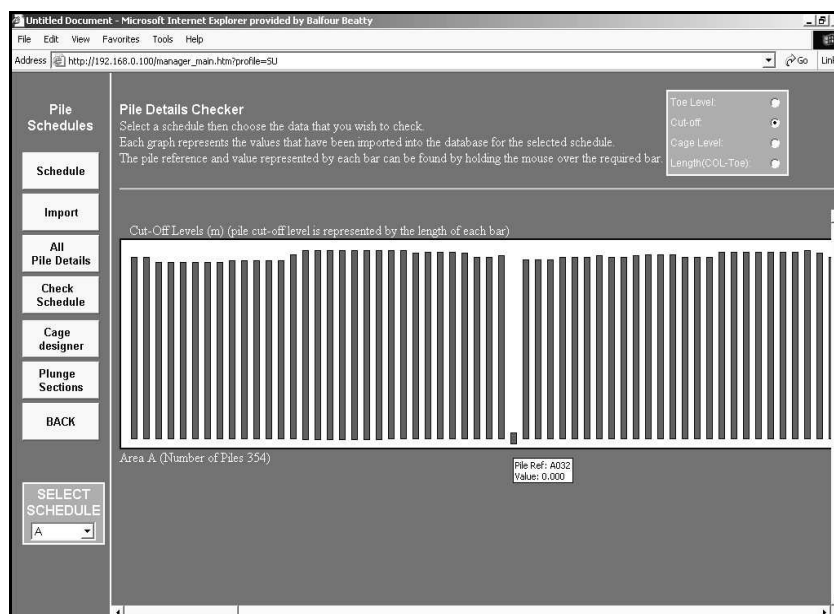


Figure 6. Histogram visualisation of imported pile schedule data

2.3.4 Reporting

The reporting section allows for the collation and viewing of pile data in HTML format. A number of reporting functions have been provided as follows.

- Pile construction logs provide concise details of each pile and its relative design data. Each pile log can be accessed by both the site engineer and client using a

variety of search criteria such as the work section, date constructed, date concreted, and date drilled.

- The underlying self-auditing logic built-in to the data capture service allows for the creation of an audit summary report highlighting piles that do not meet specification or specified construction tolerances.
- Concrete usage analysis can be carried out for individual piles, groups of piles or specific rigs based on theoretical and actual quantities used and dates of deliveries. In addition, deliveries can be analysed in respect of time variances between batch, delivery and placement.

2.3.5 Site viewer

The site viewer dynamically generates a colour-coded 2D representation of the current site status using the coordinates and diameter of each pile contained within the database. The image created includes a pan and zoom function and colours each pile according to its current status: concreted; completed; or incomplete. Each site view image is augmented with an underlying 'click map' allowing additional pile data to be accessed by clicking on the required pile via the use of a right-click menu.

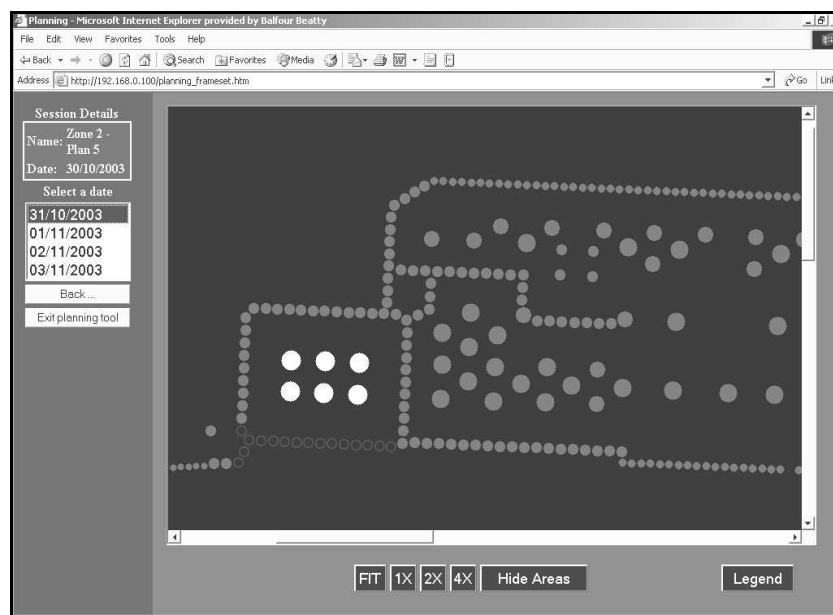


Figure 7. A dynamic 2D site representation for planning and sequencing

2.3.6 Site planner and sequencer

Based on the same principles of the site viewer, the site planner and sequencer allows project managers to create one or a number of distinct pile construction sequences (see Fig. 7). Each sequence is created by clicking on the appropriate pile and assigning a date and rig to the pile. Once a sequence has been created it can be stepped through by selecting a date within the sequence. In addition, managers can create a series of polygonal areas to add to the sequence showing inaccessible, storage, haul and piling areas. The sequencer utilises completed pile data to show all piles that have been completed and allows a comparison to be made between planned and as constructed sequences.

2.3.7 Cost analysis

A prime cost analysis for materials, plant, labour and steel can be produced based on pile production for any day or period during the contract. Income is calculated by pre-processing the tender and assigning plant, labour, concrete and steel values to each pile, whilst costs are recorded through the daily input of timesheets for labour, plant returns, concrete and steel deliveries.

Each pile is assigned a productivity factor based on tender program which relates to the number of days required to complete the pile, for small diameter shallow piles this factor may be 0.1, however, for larger more complex piles the factor could be 1.25 or even 2. As piles are completed, the daily profit, loss and productivity can be calculated and viewed in both tabular and or graphical form (see Fig. 8).

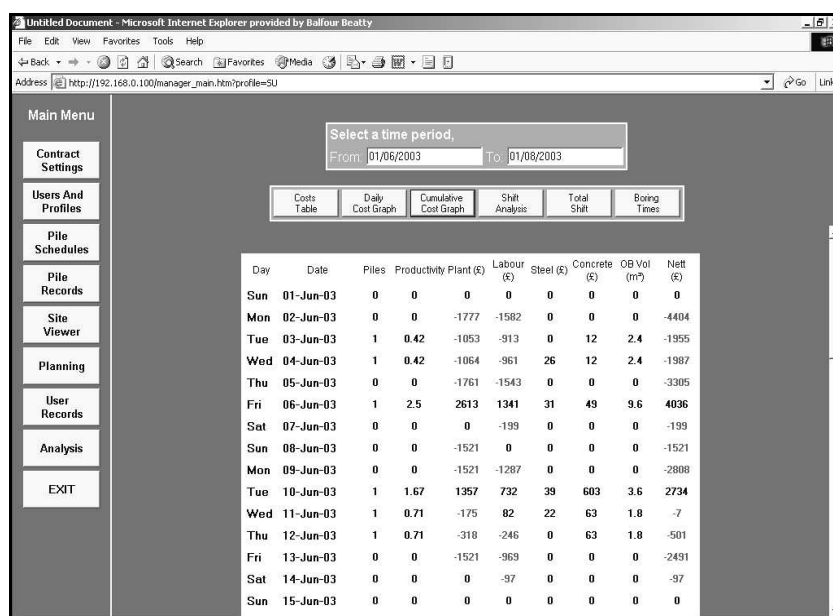


Figure 8. Prime cost analysis for a period

2.4 WIRELESS SITE NETWORK

The main enabler for the SHERPA system has been the development of a wireless site network, which extends accessibility to the system beyond the site office to the construction worker [24]. The wireless network is based on the IEEE 802.11b wireless protocol and allows for the creation of a flexible, and fully reconfigurable communications network through the use of one or a number of battery operated Wireless Network Cells (WNC). The WNC form a cellular network not dissimilar to mobile telephone networks, allowing users to communicate to the site server or peer-to-peer via one or a series of WNC. WNC are typically placed on the piling rig allowing for the creation of a work zone around the rig and have also been placed on other strategic locations such as tower cranes, when available (see Fig. 9).



Figure 9. Wireless network cells positioned on piling rig and tower crane

3 IMPLEMENTATION OF THE SYSTEM

The web-based SHERPA system has been implemented on a number of construction sites within London at White City, Arsenal and Kensington. Each site is distinct in terms of its size, complexity, duration, contractual reporting requirements and availability of services such as power and communications coverage, all of which have an effect on the implementation of SHERPA.

3.1 SERVER CONFIGURATION AND SYSTEM MANAGEMENT

In accordance with company standardisation, all server computers are supplied with a windows operating system onto which the Apache web-server, MySQL database and PHP scripting programs are installed. Due to the dynamicity built-into the web pages, server-side processing power is needed to generate the required page content, all servers are therefore equipped with a Pentium 4 CPU with a minimum speed of 2.0 MHz. All servers are located in the site office, which during piling operations can become a very dirty and dusty environment. The increased processing speed of many PC's has resulted in the augmentation of fan-cooled air intake, increasing the potential for dust ingress. Whilst this caused difficulties with early implementations of the SHERPA system, the use of environmentally controlled enclosures or PC's with integrated cooling engines have eliminated such problems.

3.1.1 Site power

By far the greatest issue regarding the use of a server on the construction site is power. Power to site offices can be via mains or provided by diesel generators, the selection of which is influenced by a variety of factors, as summarised below.

1. The location of the site offices, even on larger sites can vary depending on the status of the construction works and often relies on the availability of space during demolition and superstructure works.
2. On smaller sites, the piling operation is likely to encompass the whole of the site, requiring the site office to be continually relocated, therefore generated power is more likely to be used.
3. Whilst larger sites may be able to create a static compound for all contractors, there is no guarantee that mains power will be available.

4. The greater the number of contracting organisations on the site, the more likely a main compound will be created with access to mains power, however, this is not always the case.

During implementation, both generated and mains power have been utilised. Generators can cause power surges, which can in turn damage computing equipment. In addition they are required to be maintained once a week and in some instances are turned-off for maintenance without regard to any equipment in the site office. Whilst the provision of mains power, is not exempt from power loss, potential damage from power surges is less likely. In order to address the issue of power, each server is equipped with an Uninterruptible Power Supply (UPS), providing 30 minutes emergency power. This allows all users to be adequately informed prior to loss of service and additional emergency data capture methods deployed if required.

3.1.2 Accessibility

Prior implementations of wireless networking on piling sites [25], allowed the identification of a number of key implementation and control issues, such as:

- the creation of spoil heaps;
- the variation in working levels; and
- the commencement of superstructure work.

The experience gained from this work together with experience gained by the users resulted in no accessibility difficulties for the site workers in the implementation of the web-based SHERPA system. However, the need for additional management of the WLAN was identified in the early stages of some construction sites, due to the chaotic nature of the site.

Larger sites with many *knowledge workers*, such as White City, have allowed for the creation of a LAN in the site offices, whereas the smaller sites rely on the WLAN. No difficulties have been reported from the adoption of either method.

Direct server access for off-site personnel can be gained via the SFL corporate network or through the use of a static IP address on the server. In both cases and for practicality, the site has to have a minimum 256k Asymmetric Digital Subscriber Line (ADSL). The use of ADSL may be affected by availability, contract duration and the capacity for forward planning of the contract. Where ADSL is not provided, the web-based nature of the SHERPA system allows for the creation of a 'mirror' service located at the head office. Data can be sent from the site to the head-office on an hourly, daily, or weekly basis via a minimum 28kbps general Packet radio Service (GPRS) connection, allowing at best a near real-time view of site progress and access to site data.

3.1.3 Training

Cost and productivity restrictions within construction required that training for all personnel be undertaken on the site. Due to the accessibility and daily use of computers by *knowledge workers*, no problems were encountered in their training. Where training could not be given during working hours, *knowledge workers* typically had access to desktop computers either on the site or at home and could continue self-training in the system.

Training of construction workers had to be carried out on the site during piling works. Whilst this allowed for training on the data capture service to be undertaken in the

application environment, the emphasis on production together with staff absences through illness, movement of staff between sites by the company and the transient nature of temporary site staff, extended the training and implementation time.

3.2 MOBILE COMPUTING

Previous research has indicated that site users are less likely to utilise and accept mobile computing devices unless they are small enough to fit in their pocket, [16]. However, the nature of the construction work and users operating the system dictated that a larger touch-screen device be deployed which could be easily operated with out the use of a stylus.

Semi-rugged Windows CE tablet computers have been implemented for use by the site workforce to access the site data capture service (see Fig.10). A key driver in the selection of the device was the difference in cost, typically £900 per unit compared to £3000-£4000 per unit for fully rugged tablet device. Twenty-five tablet computers have been in operation for two years with only two failures, one involved damage to the screen, which could be repaired at less cost than purchasing a new device. This suggests that semi-rugged devices are more cost effective than fully rugged devices. In addition, the payback period is significantly less, and there is no ‘tie-in’ to justify keeping the device for longer than necessary. This is a particularly important factor in a rapidly developing market where faster, and improved devices continually emerge.

3.3.1 User integration

As the SHERPA system relies heavily on the successful implementation and operation of the data capture service at site level, the question of how to integrate the tablet computers into existing working practices was left to the site users. In response, the site users developed a system of lecterns onto which the tablet computer could be placed (see Fig. 10). This essentially resulted in the positioning of the computer at the place of work rather than individualising the units, which is a common feature of many mobile computing applications.

Unlike inspection and reporting tasks, data collection in SHERPA is time-driven and closely follows the construction sequence of the pile. As such the computers were not heavily utilised by any one person, this meant that devices could effectively be shared amongst site personnel (one per gang), thus reducing the required number on the site. In addition, the use of personalised data profiles, meant that anybody on the site could use any of the tablets distributed over the site if so wished.

3.3.2 Mobile power

Early implementations of the tablet computers, highlighted limited battery power as a major concern for site users [23,25]. Rechargeable external battery packs were therefore purchased which could provide 10 hours power to the tablet computers. The batteries could be fixed with Velcro tabs onto the back of the tablet and be connected directly to the DC input. Once the battery pack was drained, the tablet computer would automatically switch to the internal battery pack allowing for up to 14 hours use on site.



Figure 10. Semi-rugged tablet computer and use of lecterns by the workforce

3.3 SITE OFFICE COMPUTING

The construction site is rightly regarded as a dirty and challenging environment for the implementation of IT, a fact not discounted by the construction companies themselves. Many companies are thus reluctant to place IT on the site and frequently provide older disused computers for site use, this coupled with limited investment in IT caused by low profit margins, results in a large variance in the quality of computers used in the site office. Whilst such a factor may impinge on the successful implementation of desktop systems, the use of a web-based system, where data processing is performed by the server, reduces this impact, requiring only that each computer is equipped with a web-browser.

4 ASSESSING THE IMPACT OF SHERPA

Whilst the investment in systems such as SHERPA can be measured in pure financial terms such as Return on Investment (ROI) or Net Present Value (NPR), the benefits arising from the application of such systems are difficult to quantify. A number of methods for measuring the performance of WPMS have been proposed such as the Balanced Score Card and Performance Measurement Process Framework [18,19]. However, such methods have been designed with factors that are specific to WPMS such as improved communication and document transmittal between many project participants. As SHERPA has been designed to extend the WPMS to the construction site, there are a number of factors that would limit the effectiveness of such an evaluation, these being:

- the limited number of project participants;
- implementation differences between sites;
- ability for undertaking effective training on the site; and
- the limited number of sites on which SHERPA has been implemented

As such, a number of quantitative and qualitative measures have been taken to assess the impact of SHERPA as follows:

4.1 QUALITY OF CONSTRUCTION WORK

The quality of construction work is typically measured by the use of as-built inspections and snagging lists, however, such an approach cannot readily be undertaken within piling. In order to assess the impact of SHERPA on the quality of pile construction, the number of non-conformance reports (NCR's) was used as one measure. However, due to the difference in site implementations, users and piling methods, a direct comparison of non-conformances between sites with and without SHERPA would not be appropriate. The number and type of NCR's were therefore measured for a single site, before and after the implementation of SHERPA (see Fig. 11). Analysis shows a 58% reduction in NCR's across all piling sub-processes, with the greatest improvement in the positioning of the reinforcement cage. Whilst, no improvement is evident within the drilling sub-process, closer inspection shows that the NCR's raised were caused by unforeseen circumstances such as the loss of a cleaning bucket and soil conditions preventing the toe level being achieved.

4.2 WORKFORCE INTEGRATION

The following observations were made after discussions with project managers and site engineers on the contracts in which SHERPA was implemented.

The process-orientated pages and built-in self-auditing allow site workers to become aware of the main factors that affect the quality of pile construction. Where previously consideration has been on the speed of production, SHERPA has forced the site users to consider quality of construction. In addition, the SHERPA system has been used as a tool for workers that may be new to the piling discipline for learning the sequence of the construction works.

Currently, many construction workers are excluded from the information loop providing guidance on current site progress in terms other than production or work scheduling. This is particularly true of financial information, which many companies see as sensitive. Such an approach reinforces the 'them and us' attitude between site workers and their *knowledge worker* counterparts. SHERPA aims to redress this balance by allowing site managers to produce a variety of reports and graphs that can be distributed to the site workers such as analysis of production by rig or working gang and graphs showing the relationship of profit versus productivity. Such reports can be used to provide better awareness without providing commercially sensitive information to site staff, some of which may be temporary or agency based.

4.3 WORKFORCE PRODUCTIVITY

Traditionally it has been the responsibility of the foreman to complete all site paperwork. However, SHERPA now allows for data capture tasks to be carried out by a number of staff operating on the construction site. Whilst discussions with site users other than foreman would inevitably suggest an increase in time to undertake data capture tasks, it is perhaps the foreman for whom the benefit is the greatest. Typically one to two hours per day are spent by the foreman collating and completing paperwork such as concrete records, concrete tickets and pile logs. This has been eliminated by SHERPA allowing the foreman more time on the site to undertake a supervisory role.

Research into the use of tablet and wearable computers by construction workers, [10], suggests a slight reduction in productivity over those utilising paper-based documentation. However no difference was evident between daily outputs before and after the implementation of the SHERPA system. This is thought to be attributable to

the process-orientated nature of piling which provides site workers with sufficient time to complete the relatively small amount of data input required. In addition, the reduction in defects from the implementation of SHERPA and consequent delays for rectifying work are likely to be a contributory factor.

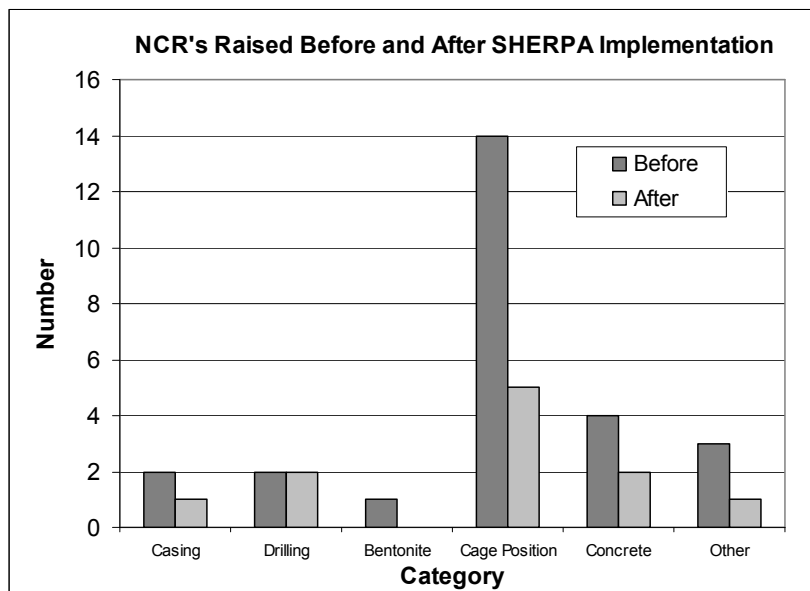


Figure 11. Analysis of NCR's before and after SHERPA implementation

4.4 IMPACT ON THE KNOWLEDGE WORKER

Site office based personnel report the greatest benefit being the improved accessibility of data coming from the construction site. The self-auditing process embedded within SHERPA speeds up the pile log checking and the sign-off process carried out by site engineers, whilst the reporting functions allow analysis using the latest available data. However, the impact of the SHERPA system on site based *knowledge workers* is perhaps evident in the number of requests made for additional services or reporting functions to be added to the system, typically 5-10 per site.

4.5 UNDERSTANDING OF SITE PROGRESS

The application of the site viewer and accessibility to cost-production reports improves the understanding of site progress not only for the site *knowledge worker* but also for those workers residing at the head office. At best, head office workers are able to access the SHERPA system in near real-time using a direct link to the site server, whilst at worst a view of the previous days progress can be achieved when the transfer of data is by GSM dial-up.

Historically, project progress and costing has been based on accounting principles, with knowledge of project financial progress limited by the valuation process. Such methods allow for the concealment of real progress by site engineers and have a distinct effect on short-term projects that may be completed before the real financial picture can be made available. SHERPA allows for better understanding of the project in both production and financial terms for all levels of the company through access to the cost analysis and site viewer services.

4.6 IMPACT ON THE CLIENT

The impact of SHERPA on the client is related to the ability and desire of the client to accept the use of electronic documentation. Whilst some large contracting companies and consulting organisations have shown an immediate acceptance of electronic records, many still insist on the presentation of paper-based documentation. The production of paper-based records can also be attributed to the contract specification, which typically dictates that paper-based records are made available by noon the day after pile construction. Whilst SHERPA provides all clients the opportunity to access pile records and progress plans over the Internet the majority of clients have requested paper-based documentation, a factor that requires addressing through the modification of construction specifications.

4.7 CONTRIBUTION TO EXISTING WPMS

Where WPMS have been implemented by the client, the integration of SHERPA has been limited to the posting of electronic pile records, a limiting factor posed by traditional document based WPMS. However, there still remains the potential to further integrate SHERPA into the WPMS such as providing links to the site server with on-click access to views of current progress via the site viewer, or access to the proposed sequence of works. A direct benefit from the implementation of wireless technologies on the construction site is the ability to access data in near-real time. Such data could in the future contribute to 4D project models allowing for improved integration between design and construction processes.

5 CONCLUSIONS

The development and implementation of the SHERPA system has highlighted the ability to extend web-based project management systems to the construction worker.

A system has been presented, providing two services which allow for the capture and management of piling data into a web-based site server in real-time over a wireless site network. Benefits to both site workers and *knowledge workers* have been highlighted which suggest a substantial improvement in the quality of work, accessibility to data and understanding of site progress. In addition, data visualisation techniques have been used to validate the importing of pile schedule data, monitor site progress and assist with pile planning and sequencing tasks.

Benefits to the client and the contribution of SHERPA to existing WPMS have been discussed. However, these are currently restricted by the acceptance of electronic documentation, restrictive specifications and the document-based nature of WPMS.

Existing communication protocols such as GSM (Global System for Mobile communications) and GPRS (General Packet Radio Services) currently prohibit the practical extension of WPMS directly to the mobile construction worker due to limited bandwidth. Whilst the future of mobile computing will potentially allow for wireless broadband access from the construction site to the head office for all users, such a concept is currently based on idealism rather than realism. Even if such technology arrives, it is likely that communication costs will be a prohibitive factor for its implementation within construction.

Whilst the example presented has been developed specifically for the piling works site, such systems have potential to deliver web-based project management support to all construction site workers in all disciplines.

6 ACKNOWLEDGEMENTS

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APPENDIX – E: PAPER 5

FULL REFERENCE

Ward M.J., Thorpe A, Price A.D.F, Wren C. (2004). The Re-use of site data to Inform Business Processes. *Proc, 10th International Conference on Computing in Civil and Building Engineering, Weimar, Germany, 02-04 June, Paper No. 26, p.76.*

ABSTRACT

The increased implementation of site data capture technologies invariably results in an increase in data warehousing and database technologies to store captured data. However, restricted use of data beyond the initial application could potentially result in a loss of understanding of site processes. This could in turn lead to poor decision making at production, tactical and strategic levels. Concrete usage data have been collected from two piling processes. These data have been analysed and the results highlighted potential improvements that could be made to existing site management and estimating processes. A cost benefit analysis has been used to support decision making at the strategic level where the identified improvements require capital expenditure.

1 INTRODUCTION

Construction site IT has been a well-researched area since the late 1980's, with applications being developed for many tasks, such as: inspection and reporting (Cox et al. 2002; Songer and Rojas, 1996; Liang, 1997); supervision (Alexander, 1997); and materials and personnel management (Baldwin et al. 1994; Escheverry, 1996). This growth in data collection applications has led to an increase in database systems required to store and manage the collected data. However, these are often built around and integrated with a specific data collection application. This effectively limits data to the primary application resulting in a lack of further re-use, because data collected on a process specific basis usually results in:

- an incomplete data set;
- inadequate database structures that do not facilitate data re-use; and
- data remaining at individual business process levels.

Even where well structured and accessible databases are available for sharing throughout the business, analysis and re-use may be limited by factors such as, time, data complexity and lack of defined mechanisms that can extract, process and analyse the data (Soibelman and Kim, 2002)

A key factor in the success of any construction company is the successful delivery of individual projects. Two business processes that have a large bearing on the level of success are estimating and site management. Whilst some data collection applications allow for the improvement of individual processes such as estimating (Kanaan and Vorster, 1998), there still remains the potential to re-use site collected data to inform the company at three distinct levels, operational, tactical and strategic.

Operational Analysis may be used by operational personnel such as project engineers, foremen or project managers to monitor, control and improve individual site processes.

Tactical Cross-contract or process specific analysis can be used for measuring and improving resource efficiency, improving accuracy of estimating, highlighting training requirements or informing decisions on the most appropriate solution for future contracts.

Strategic Driven by senior management operating at the business level, data re-use and analysis may provide information that may lead to competitive advantage or guide investment decisions.

This paper presents an example of site data collection used at Stent Foundations Limited, a major UK piling contractor. Concrete usage data have been collected from two piling processes. These data have been analysed and the results used to highlight potential improvements that could be made to existing site management and estimating processes and contribute to strategic decision-making.

2 DATA ACQUISITION

Two distinct approaches have been made by Stent Foundations in the acquisition of site data for piling works. Manual data capture by the site workforce (Ward et al. 2002), and automated data capture using on-board computers (Scott, 1999).

2.1 MANUAL DATA CAPTURE

Manual data capture is carried out for the Rotary Bored Piling (RBP) process, which is a labour intensive process comprising of four distinct phases: (1) a temporary casing is installed into the ground to support the upper levels of soil; (2) a piling rig drills through and below the casing to the pile toe level; (3) reinforcement cage and concrete are placed into the open bore; (4) the temporary casing is removed.

In order to facilitate data capture, and assist in the control the RBP process the SHERPA (Stent Handheld Electronic Piling Assistant) has been developed comprising of; (1) a site based website for project data; (2) a site based wireless network; and (3) workforce driven data capture utilising tablet computers. A site website, residing on a server in the site office, has been developed for the management and construction of rotary bored piles. The website is accessed by site management staff to manage design data, incoming site data and contract documents, such as timesheets and plant returns.

Construction workers access pile design data located on the server using a standard web browser on a Windows CE tablet computer (Figure 1) and enter as-built data as the pile progresses. SHERPA provides the user with guidance on tolerances, materials and levels for each pile, prompting and alerting users as necessary to potential non-conformances. Data entered includes dimensional information of the pile and details of concrete and steel.



Figure 1. Banksman Operating Tablet Computer

All data resides on a MySQL database located on the site server and is accessed/transferred by the workforce to the site server utilising a battery powered IEEE 802.11b wireless network. The wireless network utilises Wireless Network Cells (WNC) that allow the creation of a portable and flexible wireless networking solution without the need for a wired backbone (Figure 2), commonly seen in many wireless workplaces (Ward, et al. 2003).



Figure 2. Battery Powered WNC Installed on Piling Rig

2.2 AUTOMATED DATA CAPTURE

SIRIS (Stent Integrated Rig instrumentation System) is an automated piling rig instrumentation system used in the construction of Continuous Flight Auger (CFA) piles (Figure 3). Due to the 'hidden' nature of a CFA pile it is practically impossible to control the process by observation alone, consequently on-board instrumentation is used to ensure the production of a conforming pile.

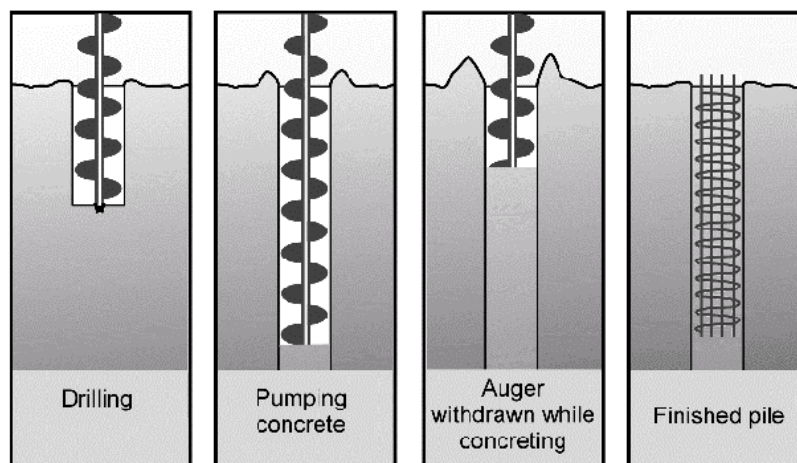


Figure 3. The CFA Piling Process

The whole process is controlled by the rig driver who is guided by an on-board touch screen computer (Figure 4). On-board sensors and meters are used to record, auger depth, concrete pressure, concrete volume and torque which are relayed to the on-board computer and presented to the rig-driver via a graphical interface.



Figure 4. SIRIS Computer Mounted in Piling Rig Cab

All data collected by SIRIS, is retained on the on-board computer in paradox tables and is automatically transferred to the head-office via Global Systems for Mobile Communications (GSM) dial-up connection at the end of each working shift. A text messaging service has also been established, allowing any staff to dial-up the rig from their mobile phone and request a status report via text message that contains the following summary:

- current operational status of the rig, drilling, concreting or delayed;
- number of piles completed in the shift;
- average overbreak for the shift; and
- total delay time.

3 INTEGRATION OF SITE DATA

Both SHERPA and SIRIS have been targeted at improving production control, with data from these systems entering the business at the operational level. Therefore, the potential for further re-use of data at the tactical and strategic levels will be driven from data analysis conducted at this level (Figure 5).

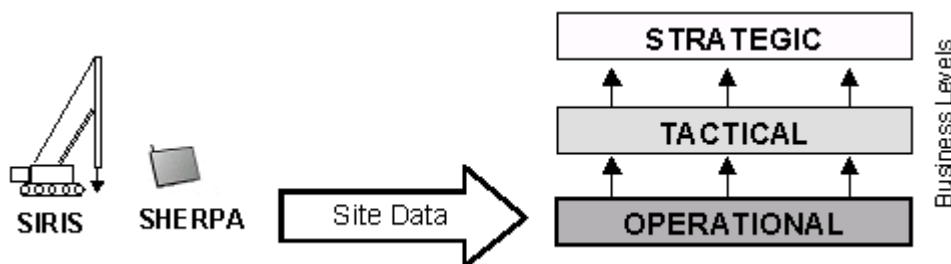


Figure 5. Integration of Site Data within the Business

3.1 OPERATIONAL LEVEL

Currently, site data re-use at the operational level, is based on known practices and experiences of individual staff operating at this level. Such practices are simplified and often have limited re-use of data which can be attributed to historical factors such as; (1) the paucity of data; and (2) time limitations for processing and analysis.

This potentially places both SHERPA and SIRIS data at risk from under-utilisation, with staff requesting data to match existing management and reporting processes.

3.2 TACTICAL LEVEL

The use of site data at a tactical level for business is extremely limited. Although paper-based site data may be available for re-use this is not integrated within the tactical level due to the following:

- Unwieldy format; and
- Inconsistent or incomplete data;

Tactical decision-making is often based on personal experience and knowledge at individual business processes such as estimating. Such knowledge may be based on out-of-date information that may lead to inconsistent decisions or inaccurate assumptions. Where data is re-used this tends to be in the form of more accessible data from costing processes. This leads to the creation of information and knowledge voids, particularly with respect to production knowledge at this level. It is therefore necessary to analyse site data to provide knowledge at this level informing estimators and middle managers of what happens at the production level.

3.3 STRATEGIC LEVEL

Due to the low profit margins within construction there is a need to justify capital expenditure at all levels, this is no truer than in Information Technology that is based on indirect benefits, which may be difficult to measure (Andresen et al. 2000). In order to justify the implementation of IT systems such as SHERPA and SIRIS, analysis of data from the systems can be carried out to justify expenditure on any potential process improvements.

4 DATA ANALYSIS

The piling industry utilises two main materials, ready mixed concrete and reinforcement. Current expenditure on concrete within the company is approximately £15 million per annum which equates to approximately 30% of company turnover, therefore analysis of concrete usage and waste has the potential to impact on company profitability. Prior to the use of SIRIS and SHERPA, such analysis has been limited, however, there now exists the opportunity to undertake data analysis from the CFA and RBP processes to generate further understanding and guide the company.

Two main factors affect the use of concrete within the CFA and RBP processes, these are overbreak and over boring. Overbreak is the percentage of concrete used in relation to the theoretical pile volume and is used by estimators and site managers for both financial and quality purposes. Over boring is the additional bored length of pile over the designed length. Table 1 shows the relationship between these factors, business

processes and construction methods. This shows that overbreak is the main measure currently used at both the operational level (site management) and tactical levels (estimating). However, over boring is not currently considered as a control measure at any level of the company, which may be due to the following factors; (1) overbreak is considered a measure of quality, whereas over boring is not; (2) lack of available data and analysis; (3) site level emphasis on production output.

The collection and analysis of site data via SHERPA and SIRIS potentially allows for improved understanding of overbreak and over boring, leading to possible improvements in site processes and estimating, and justifying investment.

Table1. The Use of Concrete Supply Factors in Business Processes and Construction

Factor	Business Levels			Construction Method	
	Operational	Tactical	Strategic	CFA	RBP
Overbreak	O	O	Not used	O	O
Over boring	Not used	Not used	Not used	Not used	O

4.1 CONCRETE OVERBREAK

When preparing tender documents, estimators include an additional overbreak volume for each pile, based on empirical measurements. This is based on the experience of the estimator with soil type being the most widely used factor. Inadequate site investigations may require the estimator to look up previous contract details from paper-based records to further inform the overbreak calculation.

Site managers use overbreak to calculate the soundness of each pile, by comparing the volume of concrete placed against the theoretical volume of the pile based on the design toe level. A large underbreak may suggest necking of the pile and a reduction in diameter placing the integrity of the pile at risk, whereas a large overbreak has financial implications for the company through over use of concrete. A simple calculation is often carried out by site managers based on design data and collation of concrete delivery tickets to provide an overbreak percentage for each pile.

Table 2 shows a summary of the data collected from SIRIS and SHERPA for the analysis of concrete overbreak. This includes the total number of piles in the data set, the period over which the data has been collected, number of rigs collecting the data and the total volume of concrete placed in the period.

Table 2. Summary of Overbreak data used in Analysis

	CFA	RBP
Number of piles	6,473	1,214
Period (weeks)	52	10
Number of rigs	8	6
Volume of concrete placed (m3)	27,000	11,000
Average overbreak (%)	23.5	11.5
Median overbreak (%)	18.2	9.6
Estimated overbreak (%)	15 - 20	15

4.1.1 CFA piling

Concrete overbreak in CFA piling is estimated between 15% - 20%, which can be attributed to the ‘hidden’ nature of the CFA process, inability to inspect the bore and placing the concrete under pressure. Concrete overbreak can be caused by too high a concrete pressure below the auger, resulting in either an expansion of the pile bore or concrete rising up the auger flight. At the start of each contract, the target overbreak percentage provided by the estimate is entered into the SIRIS system. Concrete is pumped into the pile bore below the auger, as the auger is withdrawn, the concrete replaces the void left by the auger. The rig driver utilises concrete pressure monitors and overbreak indicators to manually extract the auger at a steady rate to produce a conforming pile.

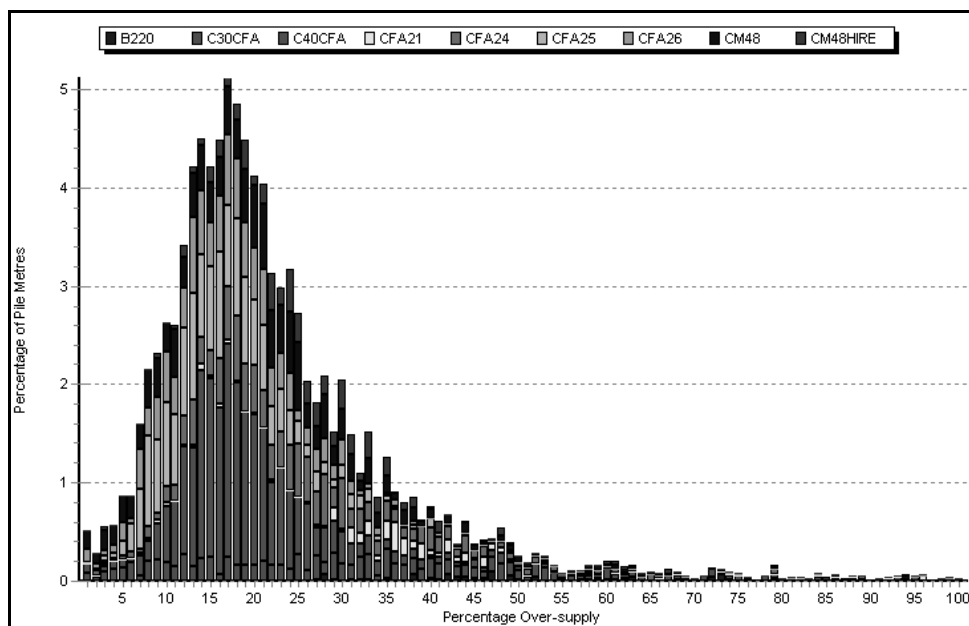


Figure 6. CFA Overbreak Distribution

Figure 6 shows a distribution of the overbreak for all CFA piles constructed for one year's production in similar soil types. The dataset has an average overbreak of 23.5%

and a median of 18.2%. The skewed distribution can be attributed to the use of a target overbreak and the tendency of the rig driver to over achieve the target. This essentially means that the drivers are adding a factor of safety to ensure a sound pile, a human factor, which is unlikely to be totally managed out through improved training or procedures. In order to counter this, an automatic auger extraction system can be implemented at a cost of £45,000; however, such investment has been traditionally hard to justify due to lack of analysis.

To justify expenditure at the strategic level, a cost benefit analysis was carried out (Table 3) which suggests a payback period for auto-extraction in less than 6 months.

Table 3. Cost Analysis for Implementing Automatic Auger Extraction

Concrete Usage (m ³)	27,000
Overbreak volume at 23.5% (m ³) (X)	6,345
Overbreak volume at 19% (m ³) (Y)	5,130
Volume of concrete saved (X – Y)	1,215
Saving per annum (at £60/m ³)	£103,275
Cost of implementation (£)	£45,000

4.1.2 Rotary bored piling

The overbreak data used for RBP is based on a single site, with predominantly clay soil. The estimated overbreak for the site was 15%. Currently site managers can calculate the overbreak percentage for each pile through the utilisation of design data that is often presented in spreadsheet format. However it is more difficult to analyse such data related to the construction process such as, the rig, driver, and crew or as constructed depths. This is because such data is located on many different documents requiring much effort on the part of the site manager.

Figure 7, shows the distribution of overbreak for RBP piling for six rigs, which shows an average overbreak of 11.5% with a median of 9.6%. This distribution indicates a more random process than that of CFA. The reasons for the variation can be attributed to a number of factors including; (1) inaccurate measurement of actual concrete volume in the pile; (2) manual measurement of pile depths; and (3) lack of automation and guidance mechanisms.

The size of the pile being excavated would be expected to have an impact on the percentage of overbreak. This is confirmed in Figure 8, which shows the distribution of overbreak with respect to 750mm, 600mm and 450mm diameter piles with average overbreaks of 9%, 7% and 17% respectively. The similarity between 750mm and 600mm piles and the large variation to 450mm diameter piles is indicative of the casing installation process used, with vibration equipment used on the larger diameters whilst the 450mm piles are pre-bored which causes large overbreaks around the top of the pile.

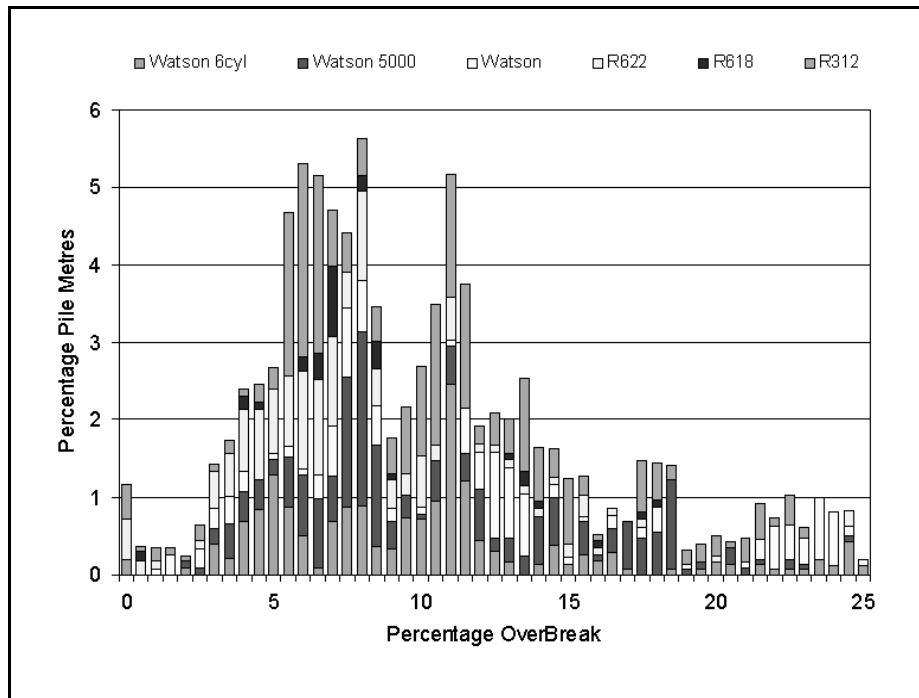


Figure 7. RBP Overbreak Distribution for Rigs

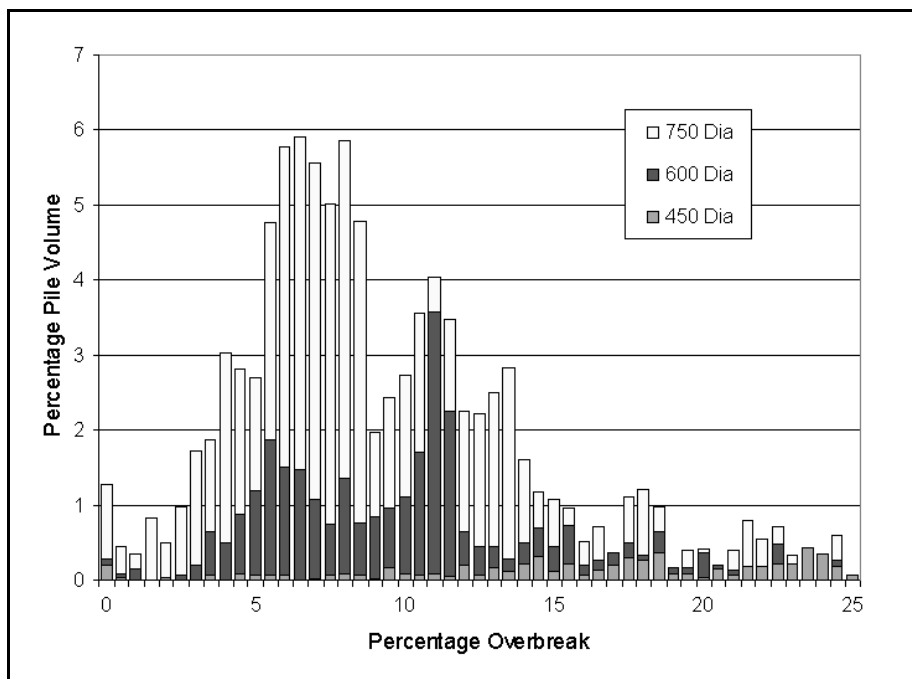


Figure 8. RBP Overbreak Distribution for Diameter

The average site overbreak compares favourably to the estimate of 15%, suggesting a net gain for the site from the over-estimation of concrete. However, it should be noted that the use of vibrating equipment was found not to be included in the original estimate. When this is taken into account the net gain becomes a loss (Table 4). This suggests that additional analysis should be undertaken to provide estimators with a cost benefit of the utilisation of vibrating equipment for the installation of pile casings,

which could also take into consideration any increased productivity from improved casing installation times.

Table 4. Net Gain from Reduced Site Overbreak in RBP Process

Concrete Usage (m ³)	11,000
Overbreak volume at 15% (m ³) (X)	1,650
Overbreak volume at 11.5% (m ³) (Y)	1,265
Volume saved (X – Y)	385
Saving (at £85/m ³)	£32,725
Cost of vibration equipment (£)	£40,000
Net Gain	-£6,750

4.2 PILE OVER BORING

Over boring is specific to the RBP process and is caused by the rig driver digging the pile deeper than necessary. The length of each auger varies with pile diameter but is typically in the range of 1.5 – 3m, requiring the auger to be dropped into the bore a number of times to reach the required toe level. After each dig the depth is measured by the banksman using a tape, whilst the driver spins-off the auger to remove the excavated soil. Payment for pile production is based on the design toe level, therefore the cost for boring and filling additional depth with concrete is borne by the piling contractor. To date, analysis of over boring has not been undertaken due to restraints in collating data.

There are many factors that affect the ability to reach the target depth of the pile such as; (1) the accuracy of taping; and (2) the ability of driver to control the auger speed and rotation. Figure 9 shows the distribution of over boring in the RBP process with an average overbore of 1.26% and a mean of 0.97% of pile depth. The total overbore length for the sample is 332m with a total overbore volume of 117 m³. The quantity of over boring not only incurs costs from additional concrete but also from the disposal of spoil, whilst the additional length of boring effectively equates to a loss in productivity. The skewed distribution is indicative of the tendency to over bore the pile and is comparable to that of pile overbreak in CFA, suggesting that the use of a target is an influencing factor in both instances.

To improve control of over boring in the RBP process, two measures can be implemented; (1) changes in bonus schemes to reflect quality of workmanship rather than productivity; and (2) the implementation of auger depth gauges on the rigs.

Bonus schemes for the site are currently based on the productivity of each rig, based on the design length of piles completed, with overbore not included in the calculation of the bonus. Analysis of the average overbore for each rig versus productivity (Figure 10) shows good correlation between productivity and over boring at 0.82. This effectively costs the company double, as they are paying bonuses based on increased productivity whilst at the same time paying for the disposal and filling of the overbore for the faster rigs. Bonus schemes are currently being revised within the company to reflect workmanship and quality. However, as over boring is not currently considered to

be poor workmanship, this would require a change in company policy directed from the strategic level.

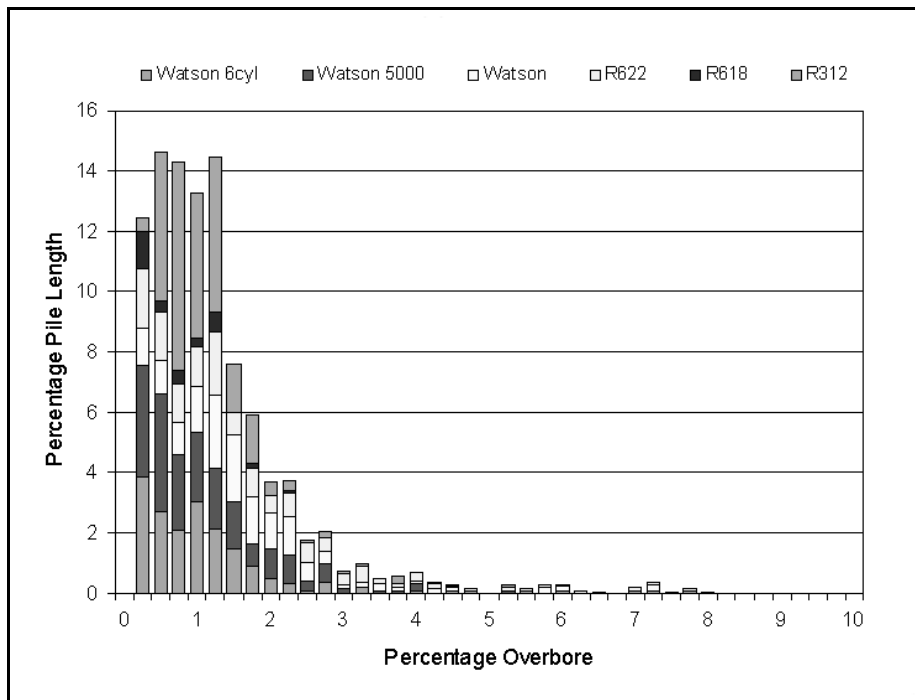


Figure 9. Distribution of over boring in RBP Process

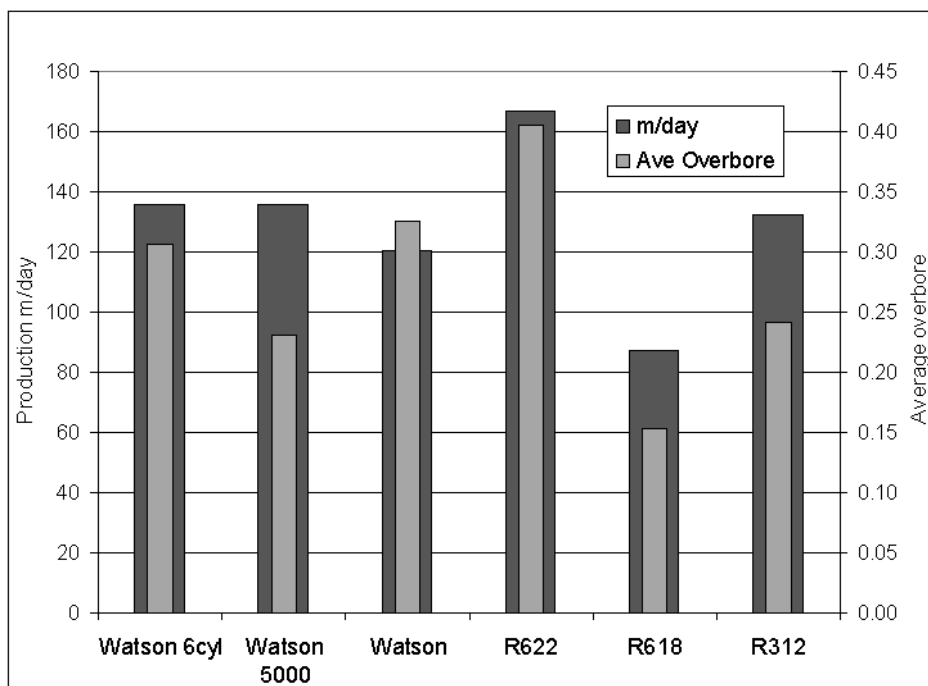


Figure 10. Relationship Between Over boring and Productivity

The potential for reduction in waste due to reduced overbore was discussed with rig drivers and foreman, who suggested that any over boring target should be based on the minimum depth that can practically be excavated in a single spin of the auger, which is 0.2m. Assuming that this average could be met, this would reduce the total overbore volume for the dataset to be 80m³, resulting in a potential saving of 37m³.

The adoption of auger depth gauges was considered a more suitable solution, as drivers would be able to see how deep the auger was so that a final dig could achieve the toe level. After discussion it was decided that a figure of 0.15m would be suitable for an average overbore based on the use of depth gauges. The cost of implementation of depth gauges across the fleet would be in the region of £100,000, however such expenditure has been difficult to justify.

Table 5 shows the volume of concrete to be saved from the site for the analysed dataset by reducing the average over boring to 0.150m. The saving of £85/m³ is inclusive of concrete costs and disposal of additional soil. When applied to the whole company, the potential annual saving would be in the region of £111,000 suggesting a payback period of just less than one year.

Table 5. Cost Analysis for Implementing Depth Gauges

	Site Dataset	Company
Concrete Usage (m ³)	11,000	250,000
Total Overbore Volume (m ³) (X)	117	2,667
Target Volume at 0.15m (Y)	60	1,361
Volume saved (X – Y)	57	1,306
Saving (at £85/m ³)	£4,845	£111,010
Cost of implementation £		£100,000

4.3 CONCLUSIONS

Data from automated and manual site systems for two piling processes were analysed with respect to concrete waste, in terms of overbreak and over boring.

Overbreak is the main measure of quality used by the company and is utilised by estimating and site management processes. Overbreak reductions within the CFA process can be achieved through additional automation, which will in turn improve estimating, whilst the RBP process would benefit from more informative estimating systems based on construction methods and productivity.

Over boring is specific to the RBP process and has been shown to have a direct correlation with productivity. Currently over boring is not seen as an indication of poor workmanship, nor is it regularly monitored, however, analysis shows that effective control of over boring can potentially save the company in excess of £100,000 per annum. Two mechanisms are proposed for this; (1) changes to the bonus scheme, requiring a change in company policy; and (2) the installation of auger depth gauges.

Where investment in new equipment has been identified, cost benefit analysis has been conducted which shows payback periods as little as 6 months.

5 ACKNOWLEDGEMENTS

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