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A new approach for optimizing earth-moving operations. Part 1

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A new approach for optimizing earth moving operations. Part I

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■ Mass-haul diagrams and experienced engineering judgement, together with deterministic methods, have been the key factors in planning and estimating earth moving operations. Although, simulation and linear/integer programming (LP/IP) models have been developed to overcome some of the limitations of these methods, those available hitherto are relatively fundamental. This Paper describes a comprehensive model produced by a combination of the above techniques in order to optimize the entire earthmoving system. The model has three stages: simulation, to provide realistic unit costs and production rates using balanced plant teams; LP/IP optimization, to provide optimum material distribution incorporating constraints such as project duration, plant availability, sequence of operations and so forth; and network scheduling providing a construction plan. The potential of the model is demonstrated in a separate paper (Part II), which outlines its application in two case studies. These demonstrate possible cost savings, minimum project completion time, the cheapest project cost and the corresponding earth moving plans achievable with the resources available.

Notation

$C_e(i, s, n)$	unit cost of excavation of 1 m ³ (i.e. £/m ³) of soil type s in cut section i by team number n
$C_h(i, s, n)$	unit cost of hauling of 1 m ³ (i.e. £/m ³ /km) of soil type s from cut section i by team number n
$C_c(i, j, s, c, n)$	unit cost of compaction (i.e. £/m ³) of soil type s from cut section i and compacted in layer type c in fill j by team n
$C(i, j, s, c, n)$	unit cost of hauling soil type s from cut section i to layer c in fill section j by team n
$C_B(p, j, s, c, n)$	unit cost of hauling soil type s from borrow pit p to layer c in fill section j by team n
$C_{SB}(b, j, s, c, n)$	unit cost of hauling soil type s from borrow pit b (to be set up) to layer c in fill section j by team n
$C_D(i, k, s, n)$	unit cost of disposing of soil type s from cut section i to disposal site k by team n
$C_{SD}(i, d, s, n)$	unit cost of disposing of soil type s from cut section i to disposal site d (to be set up) by team n

D	project duration in days
$d(i, j, s, c)$	distance in kilometres between centre of masses of strata type s in cut i and layer type c in fill j
$K_{SB}(b)$	set up cost of borrow pit b
$K_{SD}(d)$	set up cost of disposal site d
n	any plant team identification number
N	entire set of fleet identification numbers available to the contract
N_T	a set of equipment teams which share individual equipment pieces
$N_{i, j, s, c}$	a set of identification numbers of plant teams which are used to haul soil type s from cut i to be compacted in layer c in fill j
$N_{p, j, s, c}, N_{b, j, s, c}$	are defined similarly for borrow pit p and b (to be set up) respectively
$N_{i, k, s}, N_{i, d, s}$	a set of identification numbers of plant teams which are used to dispose soil type s from cut i to disposal site k or d (to be set up) respectively
$P(i, j, s, c, n)$	production (in place m ³ /day) when moving soil type s from cut i to layer c in fill j by team n
$P_B(p, j, s, c, n), P_{SB}(b, j, s, c, n)$	are defined similarly for borrow pit p and b (to be set up) respectively
$P_D(i, k, s, n)$	production (m ³ /day) when disposing soil type s from cut i to disposal site k by team n
$P_{SD}(i, d, s, n)$	is defined similarly for disposal site d (to be set up)
$Q_C(i, s)$	cut required at section i corresponding to soil type s
$Q_D(k)$	capacity limitation of disposal site k
$Q_F(j, c)$	fill required at section j corresponding to layer c
$Q_B(p, s)$	capacity limitation of soil type s in borrow pit p
$Q_{SD}(d)$	capacity limitation of disposal site d (to be set up)
$Q_{SB}(b, s)$	capacity limitation of soil type s in borrow pit b (to be set up)
$S_{i, j, s, c}^f$	swell (or shrinkage) factor in fill for soil type s excavated from cut i to be compacted in layer c of fill j
$S_{p, j, s, c}^f, S_{b, j, s, c}^f$	are defined similarly for borrow pit p and b (to be set up) respectively
$S_{i, k, s, n}^f$	swell (or shrinkage) factor in fill for soil type s excavated at cut i by team n to be disposed at disposal site k
$S_{i, d, s, n}^f$	is defined similarly for disposal site d (to be set up)
$S_{i, s, n}^h$	swell (shrinkage) factor of material being hauled from strata type s in cut i by team n
$X(i, j, s, c, n)$	quantity of soil type s moved from cut i to layer c in fill j by fleet n
$X_B(p, j, s, c, n), X_{SB}(b, j, s, c, n)$	are defined similarly for borrow pit p and b (to be set up) respectively

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$X_D(i, k, s, n)$	quantity of soil type s disposed from cut i to disposal site k by team n
$X_{SD}(i, d, s, n)$	is defined similarly for disposal site d (to be set up)
$Y_{SB}(b)$	binary variable for borrow pit b , equals 1 if borrow pit is set up
$Y_{SD}(d)$	binary variable for disposal site d , equals 1 if disposal site is set up
Z	total earthmoving cost

Introduction

Earthwork optimization in road construction has drawn considerable attention from past researchers, particularly in the USA and Canada, resulting in the development of computer simulation models to determine production output (Douglas,¹ Gaarslev,² Willenbrock,³ Clemmens⁴), and Linear/Integer programming (LP/IP) models for optimum material distribution (Shaffer,⁵ Stark,⁶ Mayer,⁷ Nandgaonskar,⁸ Easa^{9,10}). Simulation models have been developed by incorporating real life problems, stochastic variations and various types of delays, to obtain either realistic production (or cost) or a balanced plant team. This technique evolved to overcome over-estimates of production obtained from deterministic methods. On the other hand, LP/IP can be applied to obtain optimum material distribution in a wide range of applications, and were developed to remove the limitations of traditional mass-haul diagram.

2. Although, these techniques could have considerable bearing on earthwork optimization, they are often not fully developed or have severe limitations. Furthermore, the LP/IP models can only be applied to obtain an optimum material distribution including a

selection of borrow/disposal sites, but they fail to test alternate plant teams or incorporate constraints like the total project duration.

3. This Paper describes a model developed by extending the capabilities of the above two powerful techniques: computer simulation and linear programming and combining them to overcome the aforementioned limitations. The developed model was named roadwork earthmoving system optimization model (RESOM) and consists of three main stages: simulation model; LP/IP model; and network model.

Overall modelling approach

4. A typical road construction site as shown in Fig. 1 was considered and it was assumed that the following information was available

- quantities involved in each cut corresponding to different soil types
- appropriate quantities required in each fill corresponding to different soil types and degrees of compaction
- possible locations of borrow/disposal sites, their capacities and setting-up costs
- available plant teams and their appropriate hire rates or operating and maintenance costs
- anticipated project duration.

5. The main objectives of the model development were that, given the above information, the main outputs of the model should provide

- realistic unit costs of moving earth corresponding to different plant teams tested, by incorporating real life problems, interferences and stochastic variations

Fig. 1. Profile and plan views of a typical road construction project with different soil strata

- (b) optimum material quantities for cut and fill sections, borrow pits and disposal sites, corresponding to different material types and different degrees of compaction required
- (c) optimum combination of plant teams for individual haulage operations from available resources, for the entire job to be completed within a specified period
- (d) optimum combination of the plant teams from available resources to achieve the cheapest overall cost provided that the duration of the project is not critical
- (e) the minimum time during which the project can be completed given specific available teams
- (f) the total cost of earthmoving operations corresponding to the above situations
- (g) a sensitivity analysis to test the effects of plant alternatives and the variations of the project duration.

Identification of appropriate optimization procedure

6. For such optimization problems there can be more than one approach to achieve the required objectives. The existing optimization techniques were carefully evaluated to select a suitable method. The combination of computer simulation and linear programming was found to be a very effective tool to achieve the above objectives.

A sequential representation of proposed methodology

7. The proposed methodology consists of three main stages, (i.e. individual simulation, LP/IP optimization and network scheduling) as shown in Fig. 2. Each of these stages includes several steps, as shown below. Relevant steps are input at the appropriate stage.

8. *Stage 1. Individual simulation.* The following steps may be performed as part of the individual simulation.

- (a) Identify all feasible haulage operations between cut and fill sections, cut sections and disposal sites, and borrow pits and fill sections.
- (b) Identify all possible plant teams to be tested for each such operation.
- (c) Identify appropriate swell/shrinkage factors corresponding to different soil types and operating conditions.
- (d) Identify shift times, official breaks and so forth.
- (e) Perform individual simulations and obtain realistic unit earthmoving costs for each haulage operation corresponding to plant teams tested under the prevailing operating conditions.

9. *Stage 2. LP/IP optimization.* The following steps may be performed as part of the LP/IP optimization.

- (a) Identify cut quantities required along the roadway corresponding to each type of soil, and fill quantities corresponding to different types of layer or degrees of compaction.
- (b) Obtain capacity limitations of borrow/disposal sites, and their setting-up costs.
- (c) Obtain project duration and other constructional constraints.
- (d) Apply proposed LP/IP model based on the unit costs obtained in the first stage to obtain optimum material distribution selecting appropriate borrow/disposal sites, optimum plant teams for individual operations from available resources satisfying all constraints.

10. *Stage 3. Network scheduling.* At this stage the results obtained at the end of the second stage should be applied together with the sequential logic of the construction operations adopted in the LP/IP formulation in order to obtain a construction schedule.

Fig. 2. The proposed model

Fig. 3. Breakdown of earthmoving cycle

11. Each of these stages are further described in the following sections.

Individual simulation stage

12. The individual simulation stage uses a comprehensive model, called RESOMpart 1, developed for earthmoving operations involving both scraper-pusher and loader-truck operations. The following section briefly explains its development and potential. Further details of the model can be obtained from Jayawardane¹¹.

Data collection for model building and validation

13. The simulation is performed by identifying the various activities of the process and generating durations for each of these either by a theoretical distribution or a frequency histogram developed from field data. The first step in this process is the division of the earthmoving cycle into individual cycle elements. Some of the past researchers have broken down the earthmoving cycle into different degrees of complexity depending on their own requirements. The breakdown of elements adopted by the Authors is slightly different and is shown in Fig. 3. This breakdown was adopted after observing certain unforeseen delays during a pilot study.

14. All productive elements: loading, hauling, unloading and returning, can be generated by appropriate theoretical distributions or frequency histograms. Unproductive elements, such as queueing at cut and fill area, can be incorporated in the logic of the simulation model. A valid simulation model must incorporate the most significant factors affecting these cycle element times in developing cycle element time generators. This requires the collection of field data giving cycle element times corresponding to various operating conditions, analysing them to identify significant factors and

categorizing them under those operating conditions. Various types of delays can similarly be identified and quantified.

15. With the above objectives in mind, field data were collected from six large road construction sites in Sri Lanka, covering mainly loader-truck operations. In addition, data from two road projects involving both scraper-pusher and loader-truck operations were obtained from the UK, for model validation. A general description of all projects used, data collected and study durations are summarized in Table 1.

Development of input parameters

16. The field data, collected as explained in the previous section, were categorized into various operating levels corresponding to the variables recorded during data collection and statistically analysed to identify significant factors affecting the various cycle element times in order to develop input parameters for the simulation model.

17. The significant factors among the data were systematically identified using MINITAB statistical package (Ryan¹²) and are shown in Table 2. Subsequently, the cycle element times were categorized into various operating levels based on those significant factors and representing theoretical distributions were developed using Extended Control and Simulation Language (ECSL) (Clementson¹³) in conjunction with MINITAB. From the results of this analysis, the best fitted distributions were selected and the summary results for loader-truck operations are shown in Table 3. Distributions and input parameters for scraper-pusher operations were obtained from previous research (Clemmens⁴) and are shown in Table 4.

Simulation model development

18. After identifying the probability distributions and corresponding input parameters for cycle element time generators, a detailed simulation model (RESOMpart 1) was developed on an IBM PS/2 computer using Pascal. This was found to be the most appropriate language due to its flexibility to incorporate other stages of the model at a later date. The developed model was systematically verified and validated using data collected from two sites and was shown to be capable of successfully simulating both scraper-pusher and loader-truck operations. A conceptualized representation of the flow diagram of the model is shown in Fig. 4.

Some features of the simulation model

19. Some of the main features of the simulation model follow.

(a) At the start of the model, it is necessary to input information such as cut and fill data,

Table 1. Details of sites used for data collection

Purpose	Project site	Description	Data collected	Study period: days
Model development	1. Anamaduwa Gam Udawa road network (stage 1)	Contractor: RCDC Contract value: Rs. 30×10^6 Earthwork quantity: 116 900 m ³	1738 cycles of truck cycle element times, overall equipment utilization	15
	2. Randenigala Giranduru-Kotte road project	Contractor: SD&CC Contract value: Rs. 5×10^6 Earthwork quantity: 51 000 m ³	420 cycles of truck cycle element times, overall equipment utilization	15
	3. Nilwala Ganga project site 1: Bandattara	Contractor: BEC (French) Contract value: Rs. 1315×10^6 Earthwork quantity: 2061140 m ³	966 cycles of truck cycle element times and 1457 cycles of loader cycle time	10
	4. Nilwala Ganga project site 2: Wallatota		1604 cycles of truck cycles element times and 3071 cycles of loader cycle time	11
Validation	5. Anamaduwa Gam Udawa road network (stage 2)	Included in stage 1	705 cycles of truck cycle element times, overall equipment utilization	7
	6. Puttalam cement factory quarry site		295 cycles of scraper cycle element times	2
	7. A42 Measham and Ashby bypass	Contractor: Budge Earthwork quantity: 5 million m ³	Project details, material distribution, equipment utilization, production achieved	—
Experimentation	8. M40 Banbury bypass	Contractor: Wimpey Contract value: £25 $\times 10^6$ Earthwork quantity: 670 000 m ³ (tendered only)	Project details, selected material distribution, equipment teams, construction schedules etc.	—

material types, quantities involved, swell/shrinkage factors, official break times and the number of equipment teams to be tested.

- (b) Simulation period, number of replications, frequency of printouts, speed of simulation etc. are controlled at the user's discretion.
- (c) The simulation is dynamic and state changes of all entities can be seen on the screen during simulation.
- (d) Simulation can be interrupted to modify input or incorporate management decisions e.g. modifications to plant teams. These modifications can be based either on the dynamic output on the screen or intermediate printouts.
- (e) At the end of a simulation, summary results are provided giving the production, unit costs, percentage of work and idle times for various types of equipment,

queuing time, queue length histograms of hauling units, idle time histograms of loading units etc.

Application of simulation model

20. As previously mentioned, the main objective of the simulation model is to generate input for the linear/integer programming stage which optimizes the entire earthmoving system. However, the simulation model can be individually applied to determine the following.

- (a) *Production from available fleet.* Contractors tend to use plant available in-house rather than utilizing an optimum team. In these situations, i.e. given the materials to be used and its characteristics, information of haul roads, loading method etc., the simulation model can determine the production and time estimate to be expected from a given plant team.

Fig. 4. Conceptual flow diagram of the simulation model

Table 2. Summary results of factor analysis

Element	Factors tested	Significant factors
1. Loader cycle time	1. Type of loader 2. Soil type 3. Operational factor 4. Size and condition at site 5. Loader number 6. Site number	1. Type of loader 2. Soil type 3. Operational factor
2. Positioning delay	1. Size and condition at site 2. Truck size 3. Queue condition 4. Operational factor 5. Site number	1. Queue condition 2. Operational factor
3. Hauling time	1. Haul distance 2. Truck size 3. Grade of haul road 4. Road condition 5. Operational factor 6. Site number	1. Haul distance
4. Hauling delay	1. Haul distance 2. Operational factor 3. Site number	None
5. Dump and turn	1. Truck size 2. Size and condition at site 3. Operational factor 4. Site number	1. Size and condition at site 2. Truck size
6. Return time	1. Return distance 2. Truck size 3. Grade of return road 4. Road condition 5. Operational factor 6. Site number	1. Return distance
7. Returning delay	1. Return distance 2. Operational factor 3. Site number	None

(b) *Most economic loading methods.*

RESOMpart 1 can also be used to recommend a suitable loading method to be used on a hauling operation. For example, it can be determined whether push loading with one pusher, push loading with two pushers, push-pull loading or self-loading provides the most economical solution.

(c) *Optimum team type given the optimality criteria.* The model can be effectively utilized to determine the optimum team type (scraper-pusher or loader-truck) given the optimality criterion. The optimality criterion can be the cost, time, production or a combination of these.(d) *Optimum team size given the optimality criteria.* Once it has been identified that a particular type of equipment is more economical than the others (as in case (c)), the model can be used to develop an optimum team size of a particular type, given the optimality criterion.**Linear/integer programming stage**

21. The proposed methodology can be explained by considering a typical road construction project as shown in Fig. 1. Cross-sections of a road detail the different types of soil or degrees of compaction for the various layers of road; such as subgrade or sub-base. Furthermore, borrow pits and cut sections of a roadway often have different soil strata, as shown in Fig. 1, some of which may be suitable for certain layers like subgrade whereas others may be unsuitable for any fill operations. With this information in mind, the system of the model can be defined as follows.

System definition of the proposed model

22. Let N be the set of identification numbers ($N = (1, 2, 3, 4, \dots, M)$) corresponding to all the plant teams available to a contractor on a particular earthmoving project. Let $N_{i,j,s,c}$ (which is essentially a subset of N), be the possible team identification numbers to be used to

Table 3. Fitted distributions for loader-truck cycle element times

Cycle element	Treatment level	Fitted distribution: s
1. Loader cycle	1. Wheel loader, common earth with poor operational factor 2. Backhoe, common earth with average operational factor 3. Backhoe, common earth with poor operational factor 4. Backhoe, weathered rock with poor operational factor	20 + Erlang (10, 2.4, S) 4 + Erlang (7, 2.5, S) 13 + Erlang (6, 4.1, S) 23 + Erlang (2, 10.5, S)
2. Positioning delay of truck	1. No queue at cut with average operational factor 2. Queue exists at cut with average operational factor 3. No queue at cut with poor operational factor 4. Queue exists at cut with poor operational factor	10.0 + Weibull (0.4, 7.0, S) 20.0 + Weibull (0.5, 14.3, S) 10.0 + Weibull (0.6, 40.2, S) 40.0 + Weibull (0.5, 30.1, S)
3. Hauling delay	For all cases	0.0 + Weibull (0.4, 9.2, S)
4. Dump and turn	1. Good site condition with truck size 1 and 2 2. Average site condition with truck size 1 and 2 3. Poor site condition with truck size 1 and 2 4. Poor site condition with truck size 4	8.0 + Weibull (1.9, 28.5, S) 13.2 + Weibull (1.6, 34.1, S) 8.6 + Weibull (1.7, 66.1, S) 1.0 + Weibull (2.3, 83.9, S)
5. Return delay	For all cases	0.0 + Weibull (0.6, 63.0, S)
6. Hauling	For all cases	Normal with mean = 44.8 + 0.139 × haul distance and standard deviation = 137.8
7. Returning	For all cases	Normal with mean = 31.8 + 0.121 × return distance and standard deviation = 109.9

Table 4. Fitted distributions for scraper-pusher cycle element times

Cycle element	Treatment level	Fitted distribution
1. Loading cycle (scraper)	1. Loading with one pusher 2. Loading with two pushers 3. Loading, push-pull 4. Loading, elevating	15 + Erlang (4, 9.2, S) 15 + Erlang (7, 4.4, S) 57 + Erlang (5, 10.0, S) 56 + Erlang (7, 7.7, S)
2. Dump and turn (scraper)	For all cases	21 + Erlang (6, 5.5, S)
3. Travelling delay (scraper)	For all cases	0 + Erlang (1, 114, S)
4. Travelling (scraper)	1. Single engine 2. Twin engine	Normal with mean = 82 + 0.093 distance and standard deviation = 76 Normal with mean = 94 + 0.0558 distance and standard deviation = 60
5. Loading cycle (pusher)	1. Loading with one pusher 2. Loading with two pushers	15 + Erlang (4, 9.3, S) 15 + Erlang (7, 4.4, S)
6. Return time (pusher)	For all cases	20 + Erlang (4, 5.7, S)
7. External delay (pusher)	For all cases	0 + Erlang (1, 52, S)

move strata type s in cut section i to compacted layer type c (subgrade, sub-base etc.) in fill section j . Let $X(i, j, s, c, n)$ be the quantity of strata type s in cubic metres, to be hauled from cut section i to compacting layer type c in fill section j by plant team number n , which is an element of $N_{i,j,s,c}$ (i.e. $n \in N_{i,j,s,c} \in N$). If sites are available for disposal of excess material, let $X_D(i, k, s, n)$ be the quantity of material to be disposed from strata type s in cut section i to disposal site k by plant team number n ($n \in N_{i,k,s} \in N$). If additional borrow pits are available, let $X_B(p, j, s, c, n)$ be the quantity of soil to be borrowed from strata type s in borrow pit p to the layer type c in fill section j by team number n ($n \in N_{p,j,s,c} \in N$). Let $C(i, j, s, c, n)$ be the total unit cost (i.e. per cubic metre) of haul (including excavation, transportation, placement and compaction) from strata type s in cut i to layer type c in fill j by plant team number n .

$$C(i, j, s, c, n) = C_e(i, s, n) + S_{i,s,n}^h \times [C_h(i, s, n) \times d(i, j, s, c) + C_c(i, j, s, c, n)] \quad (1)$$

where

- (a) $S_{i,s,n}^h$ = swell (shrinkage) factor of material being hauled from strata type s in cut section i by team n .
- (b) $C_e(i, s, n)$, $C_h(i, s, n)$ = unit costs of excavation and haul of material from strata type s in cut i by team n .
- (c) $C_c(i, j, s, c, n)$ = unit cost of compaction of material hauled from strata type s in cut i to layer type c in fill j by team n . This unit cost is based on the bulked volume, once multiplied by a shrinkage factor the in-place rate is obtained.
- (d) $d(i, j, s, c)$ = haul distance between centre of masses of strata s in cut i and compaction layer type c in fill j .

23. Similarly $C_D(i, k, s, n)$ and $C_B(p, j, s, c, n)$ for disposal and borrowing can be defined, although these may have an additional component of unit cost of purchasing. Subscript c is not included in the cost of disposing of material because a consistent degree of compaction has been assumed for the disposal sites.

24. To include the project duration into the formulation, which in turn gives the production rate, let $P(i, j, s, c, n)$ be the in-place production (bulk m^3/day) rate for moving earth from strata type s in cut i to layer type c in fill j by team n . This quantity can be obtained by dividing the team-hire charge (£/day) by $C(i, j, s, c, n)$ (£/m³). Similarly, $P_D(i, k, s, n)$ and $P_B(p, j, s, c, n)$ can be defined.

25. When the borrow/disposal sites are at a considerable distance from the roadway, it may sometimes be economical and even necessary to

set up new borrow/disposal sites near the roadway. This may require extra money for purchasing, site preparation, construction and maintenance of haul roads, etc. These set up costs should be included in the total cost of the project if the sites are used in the optimum solution. However, as proposed by Mayer,⁷ this aspect can be incorporated by first defining 0–1 variables $Y_{SB}(1), Y_{SB}(2), \dots, Y_{SB}(n_b)$ for each such borrow pit to be set up and $Y_{SD}(1), Y_{SD}(2), \dots, Y_{SD}(n_d)$ for each such disposal site to be set up. n_b and n_d represent the number of such borrow pits and disposal sites respectively. The variable $Y_{SB}(b)$ or $Y_{SD}(d)$ is to have value zero if that site is not utilized and it is to have value unity otherwise. If the set up cost for borrow pit b is $K_{SB}(b)$ and for disposal site d is $K_{SD}(d)$, then the total cost of utilizing that site would be

(a) for each borrow pit to be established

$$K_{SB}(b)Y_{SB}(b) + \sum_j \sum_s \sum_c \sum_{n \in N_{b,j,s,c}} C_{SB} \times (b, j, s, c, n) \times X_{SB}(b, j, s, c, n). \quad (2)$$

(b) for each disposal site to be established

$$K_{SD}(d)Y_{SD}(d) + \sum_i \sum_s \sum_{n \in N_{i,d,s}} C_{SD} \times (i, d, s, n) \times X_{SD}(i, d, s, n) \quad (3)$$

where C_{SB} and C_{SD} refer to unit earth moving costs modified to account for swell and shrinkage factors, and X_{SB} and X_{SD} are earthwork quantities.

General model formulation

26. The objective usually is to minimize the total earth moving cost and complete the project within the specified time. The total cost comprises the cost of moving earth (including excavation, placement and compaction) between cut and fill sections (or disposal sites) and between borrow pits and fill sections. In symbolic form the objective function can be written as follows.

27. *Objective function.* The objective is to minimize the total earth moving cost and hence the objective function consists of all the cost terms. The individual cost components in equation 4 are

- (a) 1st term: cost of moving earth of strata type s from cut section i to compacting layer type c in fill j by plant fleet number n . The five summation symbols have been used to cover all possible plant fleets, all possible compacting layers, all types of soil, all possible fill sections and all cut sections. $N_{i,j,s,c}$ indicates a set of identification numbers of all fleets suitable for material movement from strata type s of cut i to compacting layer type c in fill j
- (b) 2nd term: summation of cost of moving earth of strata type s from cut section i to

disposal site k using plant fleet number n . Subscript c is not included since different degrees of compaction are not usually performed at disposal sites

- (c) 3rd term: summation of cost of moving earth of strata type s from existing borrow pit p to compacting layer type c of fill section j by plant fleet number n
- (d) 4th term: summation of cost of setting up new borrow pit b . $K_{SB}(b)$ is the setting up cost and $Y_{SB}(b)$ is a 0–1 variable
- (e) 5th term: summation of moving earth of strata type s from borrow pit b (to be set up) to compacting layer type c of fill section j by plant fleet number n
- (f) 6th term: summation of costs of setting up new disposal site d . $K_{SD}(d)$ is the set up cost and $Y_{SD}(d)$ is a 0–1 variable
- (g) 7th term: summation of cost of moving earth of strata type s from cut section i to disposal site d (to be set up) by plant fleet number n .

$$\begin{aligned} \text{Min } Z = & \sum_i \sum_j \sum_s \sum_c \sum_{n \in N_{i,j,s,c}} C(i, j, s, c, n) \\ & \times X(i, j, s, c, n) \\ & + \sum_i \sum_k \sum_s \sum_{n \in N_{i,k,s}} C_D(i, k, s, n) \\ & \times X_D(i, k, s, n) \\ & + \sum_p \sum_j \sum_s \sum_c \sum_{n \in N_{p,j,s,c}} C_B(p, j, s, c, n) \\ & \times X_B(p, j, s, c, n) + \sum_b K_{SB}(b) Y_{SB}(b) \\ & + \sum_b \sum_j \sum_s \sum_c \sum_{n \in N_{b,j,s,c}} C_{SB}(b, j, s, c, n) \\ & \times X_{SB}(b, j, s, c, n) + \sum_d K_{SD}(d) Y_{SD}(d) \\ & + \sum_i \sum_d \sum_s \sum_{n \in N_{i,d,s}} C_{SD}(i, d, s, n) \\ & \times X_{SD}(i, d, s, n). \end{aligned} \quad (4)$$

28. *Constraints.* The following constraints apply.

- (a) The total cut required for each soil type in each cut section should be equal to the total quantity of material moved from that section to all fill sections and disposal sites where $Q_C(i, s)$ is the quantity of material available at cut section i corresponding to soil type s . In symbolic form this can be represented as follows

$$\begin{aligned} Q_C(i, s) = & \sum_j \sum_{c \in N_{i,j,s}} X(i, j, s, c, n) \\ & + \sum_{k \in N_{i,k,s}} X_D(i, k, s, n) \\ & + \sum_{d \in N_{i,d,s}} X_{SD}(i, d, s, n). \end{aligned} \quad (5)$$

- (b) The total quantity of fill material required for each layer in each fill section should be equal to the total quantity of material

brought to that layer from all cut sections and borrow pits.

$$\begin{aligned} Q_F(j, c) = & \sum_i \sum_{s \in N_{i,j,s,c}} \sum_{n \in N_{i,j,s,c}} S_{i,j,s,c}^f \\ & \times X(i, j, s, c, n) \\ & + \sum_p \sum_{s \in N_{p,j,s,c}} \sum_{n \in N_{p,j,s,c}} S_{p,j,s,c}^f \\ & \times X_B(p, j, s, c, n) \\ & + \sum_b \sum_{s \in N_{b,j,s,c}} \sum_{n \in N_{b,j,s,c}} S_{b,j,s,c}^f \\ & \times X_{SB}(b, j, s, c, n). \end{aligned} \quad (6)$$

where $S_{i,j,s,c}^f$, $S_{p,j,s,c}^f$ and $S_{b,j,s,c}^f$ are the shrinkage factors in fill for material hauled from cut section i , borrow pits p and b respectively. $Q_F(j, c)$ is the total quantity of fill required for compaction layer c in fill section j .

29. The shrinkage factors do not usually depend on the plant team used because the specified compaction will have to be achieved.

- (a) The total quantity of material brought from each borrow pit corresponding to each soil type should be less than or equal to the capacity of that borrow pit. In symbolic form

$$\sum_j \sum_c \sum_{n \in N_{p,j,s,c}} X_B(p, j, s, c, n) \leq Q_B(p, s) \quad (7)$$

where $Q_B(p, s)$ is the capacity limitation of soil type s in borrow pit p .

- (b) The total quantity of material disposed to each disposal site should be less than or equal to the capacity of that disposal site. In symbolic form

$$\sum_i \sum_s \sum_{n \in N_{i,k,s}} S_{i,k,s,n}^f \times X_D(i, k, s, n) \leq Q_D(k) \quad (8)$$

where $Q_D(k)$ is the capacity of disposal site k . In this case the swell factor may depend on the team used because compaction is not usually required at disposal sites.

- (c) Following the pattern of Eq. (3) for borrow pits (to be established)

$$\begin{aligned} \sum_j \sum_c \sum_{n \in N_{b,j,s,c}} X_{SB}(b, j, s, c, n) \\ - Q_{SB}(b, s) Y_{SB}(b) \leq 0 \end{aligned} \quad (9)$$

where $Q_{SB}(b, s)$ is the capacity of soil type s in borrow pit b .

- (d) Following the pattern of Eq. (4), for disposal sites (to be established)

$$\begin{aligned} \sum_i \sum_s \sum_{n \in N_{i,d,s}} S_{i,d,s,n}^f \times X_{SD}(i, d, s, n) \\ - Q_{SD}(d) Y_{SD}(d) \leq 0 \end{aligned} \quad (10)$$

where $Q_{SD}(d)$ is the capacity of the disposal site d .