A comparison of devices for measuring stiffness *in situ*

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ABSTRACT: The variability between devices that measure the stiffness of a road foundation *in situ* and their accuracy are important considerations for the introduction of such field assessment methods into the construction monitoring process. The aim of this paper is to present the significant findings of recent research into the comparability of four such stiffness devices. Results have been obtained from commercial construction sites and large-scale field trials covering a wide range of material type and stiffness. In addition, controlled tests on a synthetic rubber were carried out to investigate repeatability, as well as a study to investigate the stress dependency of the computed stiffness values.

The results show significant variations in the correlation coefficients, which were shown to be dependent upon material type and construction methods. Conclusions are drawn with regard to the efficacy and accuracy of the four stiffness measuring devices and proposals made concerning their suitability for the range of site construction conditions and materials.

1 INTRODUCTION

A key functional parameter for a pavement foundation is its resilient elastic stiffness, or stiffness modulus, which is both a measure of the quality of support which it provides to the overlaying asphalt or concrete layers and a factor that determines the stresses, and hence strains, that are transmitted to the subgrade. Recent developments of in-situ testing devices have now made it possible to obtain a direct measurement of the stiffness modulus during construction. The future use of such devices for compliance testing is becoming a real possibility and ultimately may be expected to aid in superseding the use of the CBR test, considered by many as no more than a simple index test. The resistance to permanent deformation of the subgrade and overlying materials, both for construction and long-term performance, is recognised as a second key functional parameter, but it is not considered herein.

Measurements of the stiffness modulus are widely used as compliance testing for construction control elsewhere in Europe [Thom, 1993]. Although the static plate load bearing test is widely adopted, it is increasingly being replaced by the portable and quicker dynamic plate tests which are described in this paper.

The current Specification for Highway Works [MCHW1, 1993] regulates the acceptance of road foundation materials by relatively simple index tests. However, a performance-based approach would give a greater flexibility in choice of materials and aid in promoting the use of alternative materials that may be currently precluded. A field test device will ideally be able to cope with the varied materials that could be encountered, and be sensitive enough to distinguish between their contrasting performance.

The experimental data presented herein are from a recently completed research programme aimed at investigating the feasibility of a performance-based specification for subgrade and capping. The work, sponsored by the Highways Agency, aims to measure both the resistance to permanent deformation and stiffness modulus performance parameters for different UK materials. One aim of the fieldwork was to compare different in-situ stiffness measuring devices on both commercial and specially constructed trial foundations. This paper reports comparisons of measurements using four such dynamic apparatuses.

2 TEST DEVICES

To replicate construction vehicle wheel loading, an in-situ test device should ideally measure the response of: a transient load pulse of around 40 milliseconds or longer; loading applied through a bearing plate approaching 500 mm in diameter (to simulate a twin tyre configuration); and a contact stress of around 200 kN/m^2 [Fleming and Rogers, 1995]. In reality, however, the required contact stress and load pulse duration required to mimic vehicle loading on a layer at a given depth in a partially completed pavement will vary due to the stress dependency of the materials used in the pavement. Therefore some flexibility in the loading applied by a device is desirable. A brief description of the four testing devices used is as follows.

2.1 Falling Weight Deflectometer (FWD)

The FWD is well known as a pavement evaluation tool and was used during the research to provide a benchmark. It is trailer-mounted and comprises a weight that is raised and dropped mechanically onto the 300mm diameter steel bearing plate via a set of rubber cushions by in-vehicle computer control. The drop height, weight and plate size can be varied to obtain the required contact pressure, over a large range. The load pulse duration is 25 to 40 milliseconds dependent on the material under test. The applied stress and surface deflections, from up to seven radially spaced velocity transducers, can be recorded automatically and backanalysed to infer individual layer stiffnesses. However, for this work only the central transducer, which bears onto the ground through a hole in the bearing plate, was utilised. The operational procedure was the same as that for the GDP described below.

2.2 German Dynamic Plate Bearing Test (GDP)

The GDP is described in the German specification [1992]. It comprises a total mass of 25kg, and a falling mass of 10kg that loads through a rubber buffer the 300mm diameter bearing plate, within which is mounted a velocity transducer. The drop height of the falling mass is set such that the peak applied force is 7.07 kN (i.e. 100 kPa contact stress) when calibrated on a standard (manufacturer's) foundation. The force is not measured during testing. The load pulse duration is 18±2 milliseconds. It can reputedly measure in the range 10-225 MN/m^2 (there are various manufacturers who claim slightly different ranges). The device is recommended for use on stiff cohesive soils, mixed soils and coarse-grained soils up to 63 mm in size.

The operational procedure recommended for the GDP (and adopted for the FWD) is six drops on the same spot to provide a single value of stiffness. The first three drops are termed pre-compaction, to remove any bedding errors, and are ignored. The deflections of the next three drops are recorded and displayed on the readout together with the computed average stiffness.

2.3 TRL Foundation Tester (TFT)

The TFT [Rogers et al, 1995] comprises a manually raised 10 kg mass, which is released from a height controlled by the operator and falls onto a 300 mm diameter bearing plate via a rubber buffer. The total mass of the apparatus is 30kg. The load pulse duration is 15 to 25 milliseconds. The applied force and the deflection, inferred from a velocity transducer measuring through a hole in the bearing plate, are recorded automatically. The deflection derived for the material under test is determined by single integration of the velocity transducer signal to the point in time that the measured force reaches its peak. As a result, the actual peak deflection is not reported. It is stated that early trials showed this to cause only a 2% error. It currently exists as a working prototype at the Transport Research Laboratory. The operational procedure used for the TFT was the same as that used for the GDP. To match a target contact stress, more than one drop height was used and interpolation between the results was carried out.

2.4 Prima 100

The Prima 100 is a device that has been recently developed and marketed by Carl Bro Pavement Consultants (previously Phφnix), and is similar to the TFT. It weighs 26kg in total and has a 10kg falling mass which impacts a spring to produce a load pulse of 15-20 milliseconds. It has a load range of 1-15kN, i.e. up to 200kPa with its 300mm diameter bearing plate. It measures both force and deflection, utilising a velocity transducer with a deflection range of 2.2mm. The standard apparatus comes with the velocity transducer attached to the bearing plate, although for this work the transducer mounting was specially modified to measure on the ground through a hole in the plate. The device currently requires a portable laptop computer for data output and analysis, proprietary software being provided. There are currently no published data relating to its efficacy, however.

3 FIELDWORK RESULTS

Four commercial sites and two specially constructed trial foundations were assessed. The commercial sites were visited during a period of generally prolonged good weather, in contrast to the wintry conditions encountered at the controlled trial sites. The data from the trials are summarised in Tables 1 and 2. The average stiffness value for any series of tests on the commercial sites, (usually comprising 10 test locations along a 30m construction length) are also reported in Table 1. To compare the devices, the correlation coefficients (CC) were determined from trendline fitting together with the R^2 value, which is indicative of the consistency between the paired

Table 1. Summary of Stiffness Data Collected from Commercial Sites

Site	*Section*	*Formation Details* *Subgrade*	*Capping*	*Test*	*FWD Ave.* MPa	*GDP Ave.* MPa	*TFT Ave.* MPa	*GDP* *C.C.*	*R2*	*TFT* *C.C.*	*R2*
M65(1)	*1*	Soft Silty Clay	350mm Sandstone	Capp.	51	46	72	0.89	-0.47	1.4	0.02
				Capp.	40	39	54	0.95	0.49	1.32	-0.22
	2	Soft Silty Clay (embankment)		S/G	8	13	11	1.43	0.88	1.32	0.96
	3	Silty Sand (fill)	350mm Sandstone	Capp.	120	67	128	0.54	-0.62	1.05	0.08
				Capp.	142	67	145	0.47	-0.14	1.02	0.11
	4	Silty Clay (cutting)	350mm Sandstone	Capp.	111	64	-	0.58	-0.71	---	---
				Capp.	98	65	-				
M65(2)	*3*	Mudstone (fill)	350mm Sandstone	Capp.	114	74	-	0.6	0.05	---	---
				Capp.	105	60	-	0.53	0.63	---	---
A1(M)	*1*	Oxford Clay	Stabilised Oxford Clay	Stab	105	49	-	0.45	0.21	---	---
				Stab	95	52	-	0.49	-2.7	---	---
	2	Glacial Till and Chalk (cutting)		S/G	74	49	37	0.62	-0.37	---	---
				S/G	87	67	-	0.72	-0.19	---	---
Derby Southern Bypass	*1*	Mercia Mudstone Clay (cutting)		S/G	47	22	37	0.43	-1.31	0.81	0.83
				S/G	37	25	-	0.67	0.44	---	---
			400mm Sand and Gravel and Limestone	Capp.	65	39	63	0.6	0.61	0.98	0.42
				Capp.	81	40	-	0.49	-0.12	---	---
	2	As 1	400mm Sand and Gravel and Limestone	Capp.	87	51	79	0.58	-1.81	0.9	-0.22
				Capp.	82	59	92	0.7	-0.8	1.1	-0.5
	3	As 1	400mm Sand and Gravel and Limestone	S/G	65	32	-	0.47	-0.46	---	---
				Capp.	97	54	-	0.56	0.57	---	---
	4	Clay (embankment)		S/G	211	100	-	0.46	0.11	---	---

Table 2. Summary of Correlation Coefficients for the GDP, TFT, Prima 100 and FWD Data Collected from the Controlled Field Trials

Site	*Formation Details* *Subgrade*	*Capping*	*Test*	*GDP* *C.C.*	*R2*	*TFT* *C.C.*	*R2*	Prima *C.C.*	*R2*
Mountsorrel and Bardon	Silty Clay and Gravelly silty Clay	150mm Sub-Base Over upto 450mm 6F1 Capping	S/G	--- (0.59)	--- (0.83)	--- (0.96)	--- (0.922)	----	----
			Capp	0.63 (0.63)	0.38 (0.33)	1.13 (1.13)	0.53 (0.37)	0.97 (---)	0.6 (---)

Note. Capp=Capping, S/G=Subgrade, Stab=Stabilised Soil, CC=Correlation Coefficient, R^2=Goodness of Fit of Data Points. All Correlations are with FWD data except where the figures are given in brackets, in which case the correlation is with Prima 100 data. All Capping is 6F2 unless shown otherwise.

measurements. For the four commercial sites the correlation coefficients were calculated with respect to the FWD measurements, believed by many to be a representative material stiffness (Table 1). For the two trial foundations the correlation coefficients (shown in Table 2) were calculated with respect to both the new Prima 100 apparatus and the FWD (Sub-Base only).

3.1 Stiffness Magnitude and Variability

In general, a wide range of average stiffness values was measured: 8 to 211MPa with the FWD, 13 to 100MPa with the GDP, and 11 to 306MPa with the TFT. It is apparent from Table 1 that the FWD is most closely correlated to the results of the TFT, and the GDP gives consistently lower readings. This is evidenced by comparing the results from, for example, the M65 (contract 1) at Sections 1 and 3, where it appeared that all three devices gave similar values on the capping over a clay subgrade but that the FWD and TFT measured an improvement of 100% or more on the (nominally similar) capping over the sand fill embankment. The GDP did not reflect such an improvement, although it did show a significant increase. Another example is found at M65 (contract 2), Sections 2 and 3. Section 2 showed generally good agreement between the FWD and GDP, for testing on both the subgrade and capping, whilst at Section 3 (capping only) the FWD records stiffnesses that were greater by more than 60%.

Figures 1 and 2 have been produced to show the typical variation of results along a nominally consistent construction.

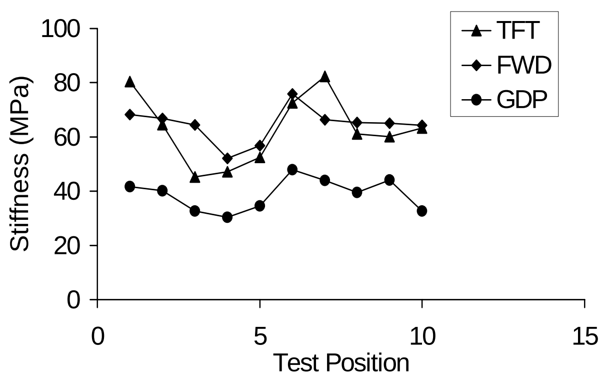

Figure 1. Variability of Stiffness Along a 20m Test Length at the Derby Southern Bypass (400mm Capping over Clay in Cutting)

Figure 1 shows measurements on a 400mm thick capping using all three stiffness measuring devices at ten approximately equally-spaced locations along a 20m test length. It shows reasonable parity between the FWD and TFT, whilst the GDP is consistently lower but follows the same general pattern with test location.

Figure 2 presents measurements on a 350mm thick sandstone capping over a clay embankment (classified as 'soft'). The test locations were at 4m intervals along the route, each device being used to measure at three immediately adjacent positions. Thus the 30 data points represent 10 test locations over a length of construction of 36m.

The TFT gave consistently higher values than the FWD or GDP. When it is considered that there are groups of three adjacent positions (i.e. positions 1, 2, 3 and 4, 5, 6 and so on) the TFT produced significant scatter of up to 40MPa by relocating the test only one plate diameter away. The FWD and GDP showed good agreement for some positions, and a reasonable consistency along the construction length with the majority of data in the range 40 to 60MPa.

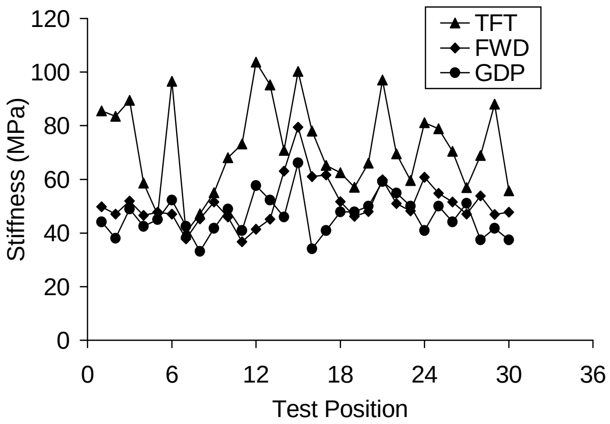

Figure 2. Variability of Stiffness along a 36m Test Length at the M65 (Contract 1) (350mm Capping Over a Soft Clay Embankment)

3.2 Correlation Between Devices

Correlation coefficients for the four commercial sites indicate that correlations are significantly site specific. The GDP gave a correlation coefficient in the range 0.43 to 1.41, with the majority in a band from 0.46 to 0.70. The TFT was found to correlate more closely to the FWD, with a range of values from 0.81 to 1.40. In addition, seven out of the ten TFT data sets were within ± 20% of the FWD readings. However, the R^2 coefficient shows in general poor consistency between the pairs of data. An R^2 value close to 1 (+ or -) is an indicator of a very good fit. The TFT data sets had 4 out of 10 values greater than 0.5 (+ or -). The GDP exhibited generally poorer fits with only 8 out of 30 values in this range. Thus, the correlation coefficients are useful for comparing sets of data, but it is suggested that applying them directly at individual points is inadvisable from the R^2 analysis.

Table 2 presents the combined data from the controlled trial foundations where the Prima 100 device was also used. The correlation coefficients for the TFT and GDP with the FWD are shown to be similar to those for the commercial sites. The relationships remain relatively consistent for both the subgrade and granular sub-base tests. In addition, the R^2 values suggest relatively good consistency, with values closer to unity for the subgrade than the overall foundation.

3.3 Stress Dependency

Figure 3 presents the results of a study of the stress dependency of the compacted granular materials and the subgrade soils for one of the trial foundation sites. The figure shows that the applied stress varied from approximately 35 to 120 MPa with the Prima and TFT, with a strong stress dependency for the tests on granular sub-base, as expected. The FWD measured no change in stiffness over its (higher) applied stress range. The FWD minimum stress is restricted, due to the self-weight of the drop assembly, to approximately 100 kPa and here was in the range 130 to 325kPa. The FWD stiffness agrees reasonably well with those for both the TFT and Prima at their higher stress. The GDP readings are approximately half those of the other devices, as was generally found with the other field data. For the tests on the subgrade the Prima showed a small increase with applied stress, whereas the TFT showed a strong stress dependency and more so than for the granular material. However, the subgrade at this trial site has appreciable gravel content in the clay matrix. The GDP again produced readings that were approximately half the value of those from the other devices.

3.4 Repeatability Tests on Rubber

To assist with determination of the sources of error, and in an attempt to control the variability of the test material, measurements were made on layers of 25 mm thick rubber (Shaw hardness 60). Up to three layers were tested with the TFT and GDP when placed on a reinforced concrete floor in the laboratory. Similar tests were carried out using the FWD with the rubber layers placed on a rigid pavement structure. Figure 4 presents the average values from 100 repeat drops for these tests and includes error bars that represent one standard deviation.

The TFT produced the largest scatter, a large difference between the responses of the different thicknesses of rubber, and a strong stress-dependency of the measured stiffness for one layer of rubber. The FWD results, in contrast, show a consistently high stiffness for all three sets of tests. Although not shown, the FWD measured only a small change in stiffness from an increase in the applied stress over the range of 100 to 200kPa. The GDP, restricted to one applied stress, showed a significant change in the stiffness response for the different thicknesses of rubber, although to a lesser extent than the TFT.

4 DISCUSSION

4.1 Field Trials

In general the TFT stiffness was found to equate to between 0.8 and 1.3 times the FWD stiffness, whereas the GDP stiffness was found to equate to between 0.4 and 0.7 times the FWD stiffness.

The variability in measured stiffness, for any one series (i.e. the same construction), was quantified by normalising the standard deviation to the mean of the test values expressed as a percentage. In general, greater variability was observed for tests on the natural sub-formations encountered than for the more controlled capping materials. The variability for the sub-formations was generally in the range of 25 to 60% for the FWD and the TFT, and in the range of 20 to 50% for the GDP. For the capping the variability was generally in the range of 10 to 35% with the FWD (notwithstanding the M65(2) data), 20 to 40% with the TFT and 20 to 40% with the GDP.

Where capping was placed over the sub-formation and tests were carried out on both layers at the same location, an improvement in stiffness was evident and a modular ratio of 1.65 determined. However, it was also evident that a clay sub-formation (as at DSB Section 4) can give greater stiffnesses than a thick layer of granular capping.

The fieldwork has shown variability in measured stiffness with any one device, and between devices, when tested on both the various constructions and also for immediately adjacent test positions. This was considered to be a significant finding in the context of their proposed use in site compliance testing. Whilst there appears to be no obvious rationale behind these

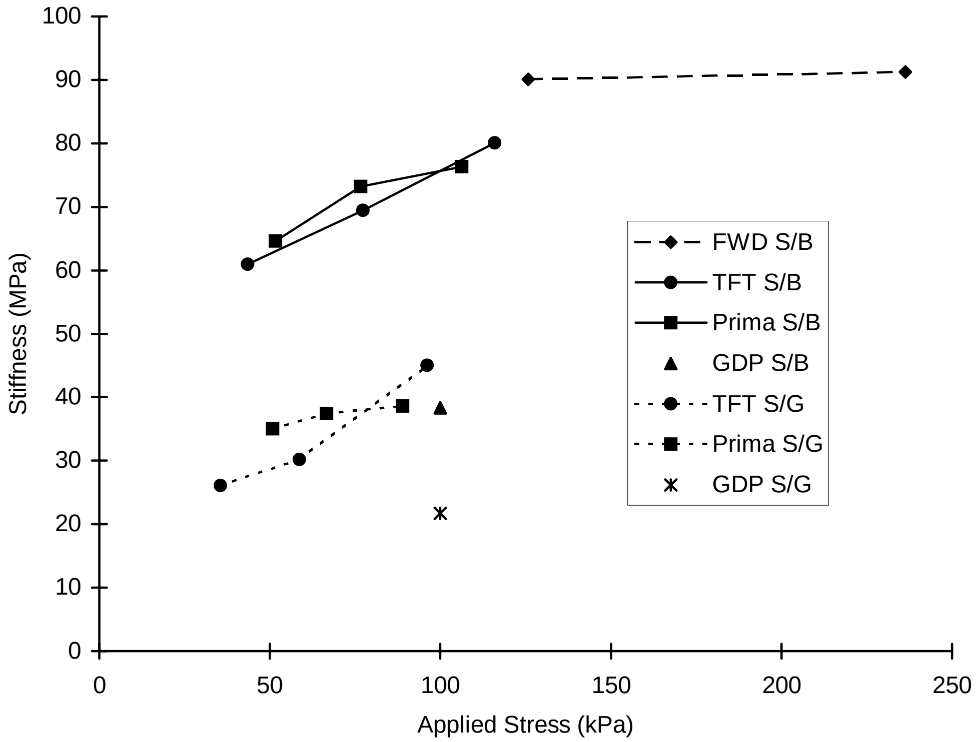

Figure 3. Relationship between Stiffness and Applied Stress for the FWD, TFT, Prima 100 and GDP on Sub-Base (S/B) and Subgrade (S/G) at a Controlled Trial Construction Site (400mm Capping and 150mm Sub-Base over a Clay Subgrade)

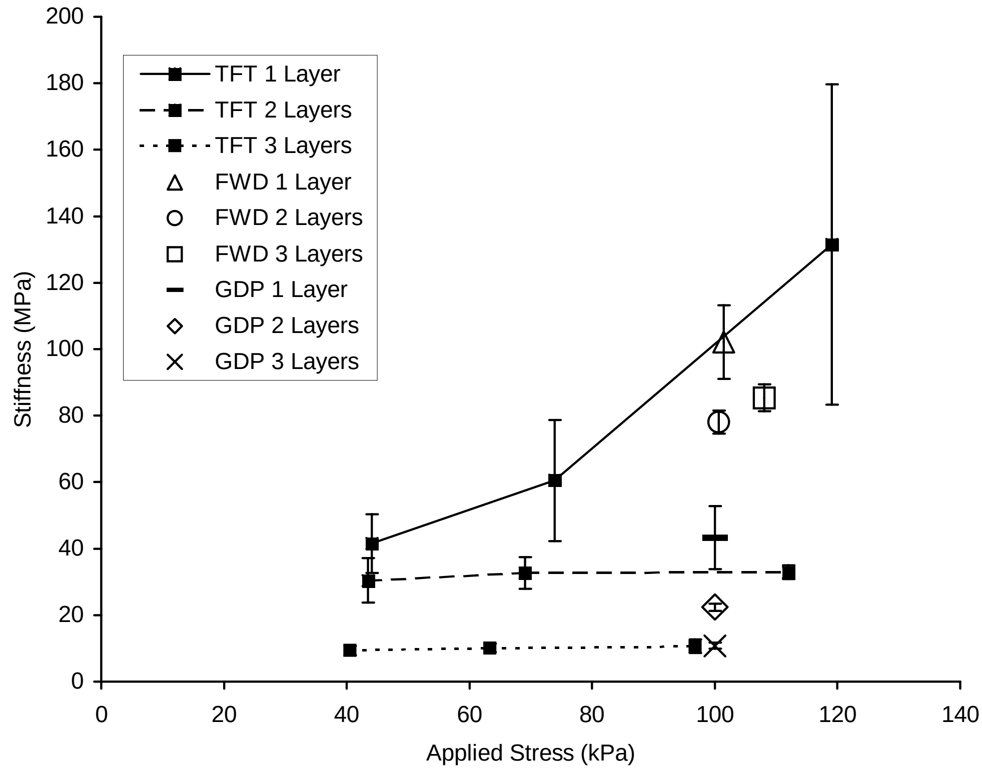

Figure 4. Relationship between (Average) Stiffness and Applied Stress for 100 Repeat Test Drops with the GDP, TFT and FWD on Three Different Thicknesses of Rubber (Note. 1 Layer = 25mm. Error Bars = 1 Standard Deviation)

relationships when considering any one measurement, it is evident that some patterns have emerged and that it would be possible to assess performance by considering the average results from a series of tests at any one site.

4.2 Stress Dependency

The stress-dependent nature of both soils and granular materials complicates the comparison between test devices that apply different contact stresses. The variation in the rate of loading is also likely to have an effect due to the variation in the stress distribution induced in the test material(s). Thus, the surface measured deflection is an accumulation of these complex, inter-related effects. If measurements are made on site during construction and are to be compared to an absolute target value, then this needs to be taken into account. It would appear prudent therefore to carry out careful trials either prior to or at the beginning of the contract to define the material behaviour. If the TFT, GDP or Prima device is to be used, it would equally be prudent to correlate these devices with either static plate or FWD tests to improve confidence, whilst bearing in mind the different levels to which the stress is transmitted in these tests.

4.3 Repeatability

It is considered that the different response measured by the FWD on the rubber may be due to the large static pre-load that it applies. When the trailer is positioned the hydraulic rams lower the bearing plate and, to ensure good contact and stability during testing, partially lift the whole trailer assembly (which weighs several hundred kilograms) thus statically loading the material under test. Thus the rubber is being pre-stressed by perhaps 50kPa or more before the *additional* transient stress is applied. This is thought to have contributed significantly to the high stiffnesses recorded by the FWD.

The TFT stiffnesses for two and three layers of rubber are much closer to the GDP stiffness and show no stress dependency, as expected. The single layer results are puzzling, however, and are perhaps due to the method of determination of the maximum deflection, as discussed below. However the increase in stress from 40 to 120 kPa caused an increase in stiffness from 40 to 120 MPa, which suggests that the deflection remained constant. This effect may also have been caused by the interaction of the rubber and the velocity transducer, which is free to move within the protective housing without restraint (i.e. it can bounce). The FWD transducers are restrained by springs to ensure that they remain in contact with the material under test. The GDP transducer is fixed within the plate.

4.4 Stiffness Interpretation

The devices all utilise simple static elastic theory to interpret an elastic stiffness modulus from the measured (or assumed) values for contact stress and indirectly measured deflection. Dynamic effects are thus not taken into account. As the measurements are made only on the plate, or on the ground directly beneath the plate, the response of the underlying (interacting) layers is thus superimposed to produce a single surface deflection value. The stiffness is therefore usually termed the foundation, or composite, elastic stiffness modulus. The surface deflection is, however, a complex function of the stress, and hence strain, distribution within the layers. Their interaction is further complicated by the stress-dependent behaviour of soils. Variations in the applied stress and load pulse duration would thus be expected to cause differences in results.

An important difference between the GDP and the other devices is that the GDP measures the change in velocity (and by integration the deflection) of the bearing plate itself, as opposed to the material under test. This alone is not expected to cause the discrepancy frequently observed between the GDP results and the other devices, although during the development of the TFT this was thought to cause a significant difference. The GDP also assumes a contact stress and this is thought to be a major source of error, which is dependent on the stiffness of the material under test. The GDP signal processing (i.e. smoothing, digitising and interpretation) may be responsible for the primary source of the discrepancy, however.

The TFT also has a specific difference to the FWD and Prima 100 in that it calculates the stiffness using the peak force and the deflection *at the point in time* of the peak force. Thus, if a time lag exists between the peak force and the peak deflection (i.e. due to inertia effects) then the TFT will *underestimate* the deflection and *overestimate* the actual stiffness. This can perhaps be observed by the correlation coefficient being greater than 1.0 in many cases.

Fleming [1999] showed that the deflection of the bearing plate is often out of phase (in time) with the applied contact stress. This lag increased with an increase in bearing plate mass (i.e. plate inertia), with an increase in the stiffness of the rubber damper used, and with an increase in stiffness of the test material (i.e. soil inertia). It should be noted however, that this work was restricted to tests on 500mm thick granular material. The study concluded that the maximum interpreted deflection should be utilised in the calculation for stiffness, and that the contact stress should be measured as it varies with the stiffness of the test material.

5 CONCLUSIONS

The research data presented herein demonstrate that there are several potential difficulties in using a dynamic plate test for compliance purposes:

- It is not sufficient merely to specify an applied load and plate size for the test method. For reasons yet to be fully understood, results from different devices can be dramatically different. Some of this difference can be attributed to different loading pulse shapes, while some may be attributed to the function of the measurement transducers or the way in which the measurements are converted into displacement.
- Any specification for assessment of stiffness *in situ* has to take proper account of the expected variation in the modulus of a foundation from one point to another and the effects of variations in applied stress (or rate of loading) on the material behaviour.
- A site-specific correlation is considered to be achievable and could be relied upon in a specification. Commercial implementation of stiffness measurements should, however, consider a pre-construction trial to assist with setting target values and acceptable limits of values for proof testing purposes.
- The TFT velocity transducer should be restrained, by a low force, to ensure consistent contact with the ground and should utilise the integrated maximum deflection in its stiffness calculation routine.
- The FWD static pre-loading of the test material may produce a significant influence on the results of testing at low transient stresses and on relatively low stiffness materials.

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