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Earthworks — if stiffness is important specify and test for it

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Abstract

Civil and geotechnical engineers routinely develop specifications for earthworks associated with civil structures (industrial warehouses, buildings, embankments, pavements, dams, reinforced earth retaining walls etc.) with the intention usually of controlling the stiffness and strength of the material in its as placed condition.

This paper focuses on the stiffness of the landform resulting from the earthworks, where the term stiffness is used to describe the deformation behaviour of the material when subjected to loading.

It is the authors' experience that the indirect methods of controlling stiffness rely on a combination of material, placement, compaction, moisture and earthworks control requirements. Furthermore, such requirements do not, under all circumstances, control the in situ stiffness of the soil.

This in turn can result in earthworks requirements being specified which are not necessary to result in adequate stiffness i.e. over specification; or earthworks requirements which do not necessarily result in adequate stiffness being specified, i.e. under specification.

Furthermore, the typical earthworks specification has not changed much in 40 years, yet the typical performance requirements for superstructures supported on the earthworks have changed. On this basis, what in the past may have been 'stiff enough', may not be adequate and then for other uses may be grossly over specified.

It is the authors' opinion that the above issues can be addressed by direct measurement of the stiffness. Such measurements need to be understood within the limitations of characterising complex soil behaviour using simple models, e.g. elastoplasticity.

This paper presents six case studies where direct measurement of stiffness assisted the authors in addressing the limitations discussed above. Further, it presents results of stiffness measurements taken by means of plate load testing, settlement plates, large-scale oedometers and large-scale loading tests.

The authors hope that the paper will encourage practitioners to 'specify and test for stiffness where it matters'.

1 Introduction

Civil and geotechnical engineers routinely develop specifications for earthworks associated with civil structures (industrial warehouses, buildings, embankments, pavements, dams, reinforced earth retaining walls etc.) with the intention usually of controlling the stiffness and strength of the material in its as placed condition.

This paper focuses on the stiffness of the landform resulting from the earthworks, where the term stiffness is used to describe the deformation behaviour of the material when subjected to loading.

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This paper presents by means of six case studies, some of the limitations arising from the described approach and how in the authors' experience direct measurement of stiffness can address these limitations.

2 Direct measurement of soil stiffness

Stiffness of fill can be directly measured, and the authors have been doing so using combinations of the points made in the following paragraphs of this section.

Large-scale oedometer tests (Figure 1). Using a load frame that allows pressures of up to 1 MPa to be applied on a sample with diameter 300 mm and height of 200 mm, it is possible to test the response to loading of a representative sample of the earth fill materials. The more usual oedometer tests undertaken on samples sizes less than 75 mm diameter often result in significant portion of the earth fill materials having to be removed from the sample tested.

Figure 1 Large-scale oedometer test set up. Sample diameter is 300 mm

Plate load tests (PLT). Plate load tests are tests in which load is applied and released in increments to a circular plate, with the load on and settlement of the plate being measured. The authors undertake the test on plates with diameters of 300, 500, 750 and 1,000 mm. The counterweight of an excavator is typically used as reaction for the testing, although purpose made reactions (such as a reinforced concrete 'horse') have been used. The settlement of the plate during loading and unloading is measured at the centre of the plate, relative to the fixed referenced beam. Standard methods for plate load testing are available, for example ASTM D1196-93 (1997). A simplified plate load test apparatus and procedure has been used by the authors over the last 12 years (Shen & Mostyn 2012). A photo of the test set-up is shown in Figure 2.

Figure 2 Simplified plate load test set up using a 1 m diameter plate

Large-scale in situ load tests. These refer to testing of the landform in place by applying, and usually removing, the load using for example soil or brick pallets and measuring the deformation response (Figure 3).

Figure 3 Example of large-scale in situ load test using brick pallets and precise surveying

3 Controlling stiffness by earthworks specification

Since the 1930s, practice with earthworks has been to essentially control material type and placement compaction to achieve a landform with the desired stiffness and strength. This approach is reflected in the relevant Australian earthworks standard (Standards Australia 2007). Comparison of the suggested earthworks controls in AS3798-1990 and AS3798 (Standards Australia 2007) indicate very little change in the earthworks control approach in that time.

It is the authors' experience that most specifications indirectly control stiffness by requirements addressing:

- Material type.
- Placement layer thickness.
- Compaction.
- Moisture content.
- Earthworks control regimes (performance specifications with in situ density testing, or method specifications with number of passes).

Experience indicates that certain combinations of the above result in adequate stiffness for certain types of developments and fill. It is the role of the earthworks designer to ensure that earthworks completed in accordance with its specification result in the required performance. Given that the above are at best indirect measurements of stiffness, ensuring performance using the above controls can result in over-specification.

4 Some issues arising from controlling stiffness by earthworks specification

Some issues with this approach, which the authors have identified over 40 years' experience, are:

- Over-specification resulting in unnecessary exclusion of materials.
- Potential over or under-specification due to increased performance demands with regards the earthworks. Earthworks specifications have not changed much in the last 40 years but performance requirements have. How do we advise regarding expected performance of landform in terms of stiffness where increased demands do not allow the designer to rely on previous

experience to ensure its stiff enough? Direct testing of the stiffness allows the specification to be tailored to the increased requirements without over-specification.

- The specification approach simply not controlling the stiffness with enough certainty not to result in poor performance. This is particularly true where the performance of the structure relies heavily on the stiffness/deformation properties of the earthworks, e.g. ground-structure interaction problems.

Case studies A to E present practical examples of how direct measurement of stiffness has been used or could have been used to overcome the above hurdles.

5 Case studies

5.1 Case study A — ripped sandstone at Enfield Brick Pit

In early 2002, the authors were commissioned to provide advice regarding filling of the decommissioned Enfield Brick Pit in Sydney's inner western suburbs. Enfield Brick Pit had a surface area of 40,000 m^2 and was up to 40 m deep. The owner of the pit proposed to fill the brick pit with virgin excavated natural material (VENM) to produce a final landform for immediate residential, commercial or light industrial development (Piccolo & Mostyn 2007).

The design of the earthworks required placement of ripped sandstone fill at the base of the pit to form a stiff layer to, in part, even out long term differential settlement due to the uneven geometry at the base of the pit.

Ripped sandstone fill is recognised as one of the best fill material, available in Sydney. When well compacted, it produces a stiff, strong layer with low susceptibility to creep and inundation strains. However, a typical earthworks specification that includes controls on maximum particle size, requirements for in situ laboratory and compaction testing can result in the material being essentially excluded, or requiring significant processing, if the specification is strictly applied.

The material is often too coarse for in situ or laboratory testing and larger particles which do not break down under compaction equipment can be present.

Rather than excluding the sandstone, a specification was developed which required material to be placed in 300 mm layers and compacted to achieve a target minimum in situ modulus of 40 MPa as measured using point load tests (PLTs). Spreading of the sandstone fill was undertaken using a CAT825 compactor, which also provided some compaction. The fill was then further compacted using a 25 tonne vibrating pad foot roller. Control of the sandstone compaction was undertaken using PLTs.

A total of 162 PLTs were conducted on the ripped sandstone fill. Twelve of which were conducted on sandstone fill poorly compacted for comparison reasons. The assessed moduli are presented in Figure 4.

An additional 34 tests were completed on residual clay VENM fill placed on site. The clay was placed as per a typical specification and a compaction ratio of at least 98% SMDD. The plate load testing was undertaken to assess the relative stiffness of the clay fill versus the ripped sandstone fill as a guiding index to the long term behaviour of the clay fill. The PLT results on the clay fill are also summarised in Figure 4.

5.2 Case study B — blending topsoil with residual shale VENM

Clause 4.2 of AS3798 includes topsoil as an unsuitable material (Standards Australia 2007). Many specifications will exclude topsoil from use in structural and sometimes even landscape fills. Experience in industrial subdivisions in Sydney's west and south-west highlighted the significant cost of disposing of topsoil from what are otherwise carefully balanced cut and fill projects.

The reason for excluding topsoil is that it is seen to impact on the strength and stiffness of the landform. The authors and their colleagues have used direct measurement of stiffness in terms of plate load testing to quantify the effect of the topsoil and design landforms which can include a certain percentage of topsoil.

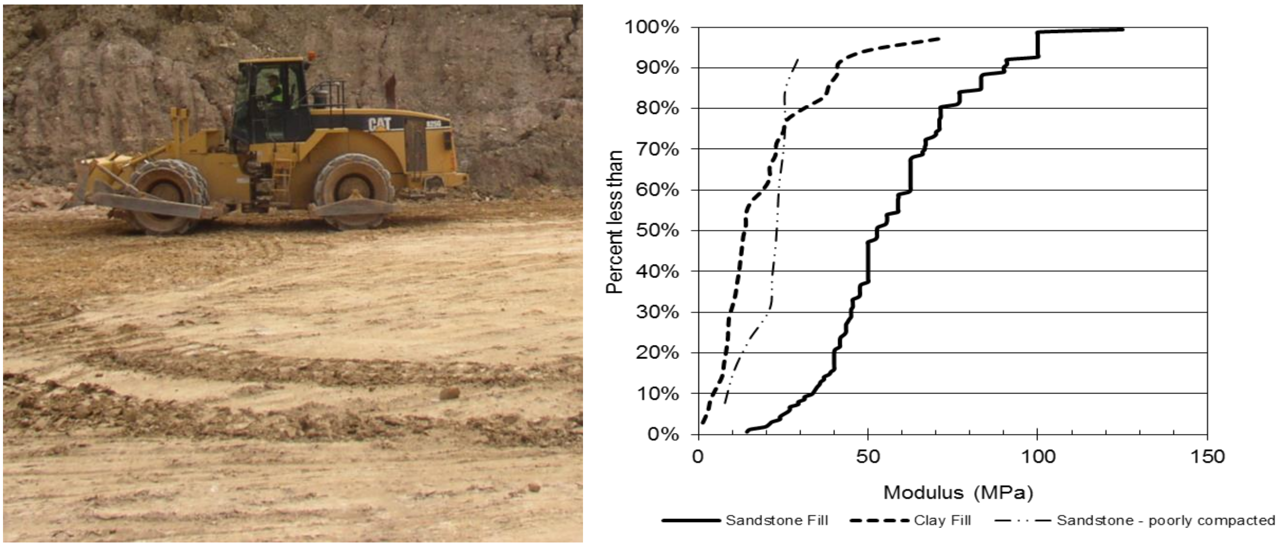

Figure 4 Photo on left shows sandstone fill subgrade. Chart on right provides distribution of test results on sandstone and clay fill

On four separate sites, tests were completed on landforms comprising well compacted clay/shale fill with between 10 and 20% of topsoil blended into the fill. The results of the plate load testing for each site are shown on Figure 5.

Whilst the initial assessment that topsoil will impact on the stiffness is correct, by quantifying the impact it was possible to design a landform that included a proportion of topsoil whilst still delivering the required performance.

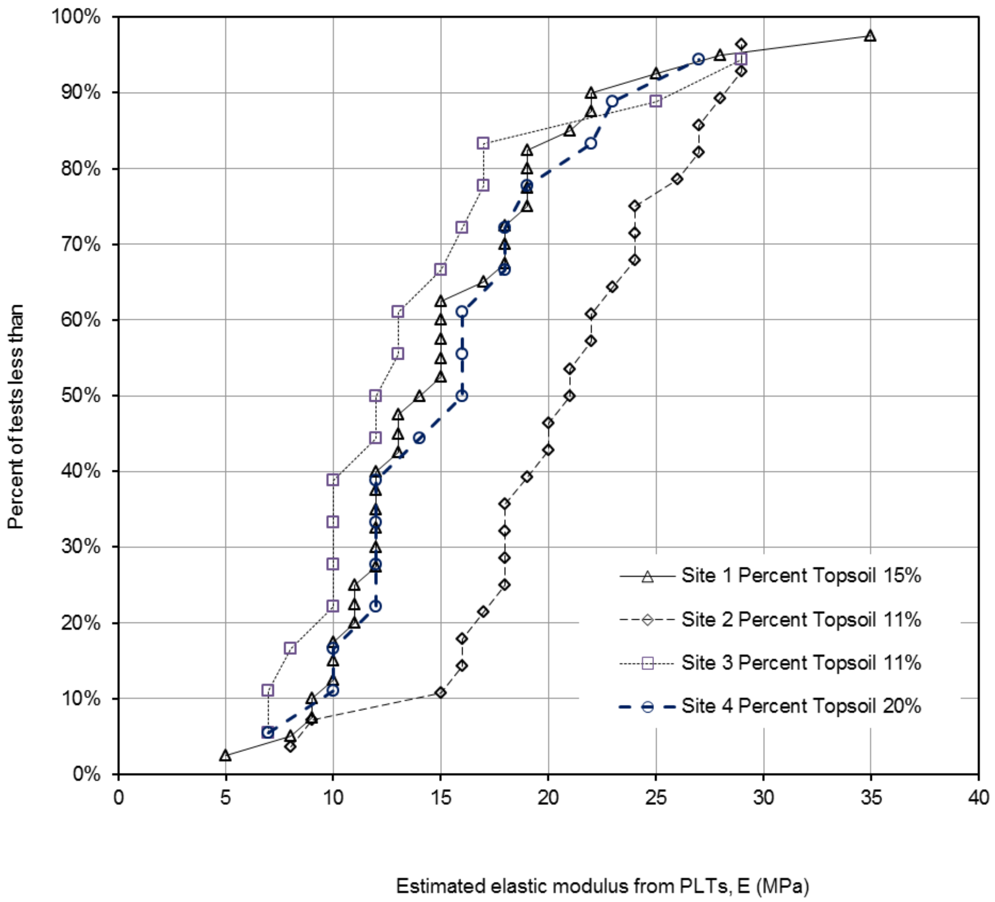

Figure 5 Summary of plate load test results on shale/clay fill blended with between 10 and 20% topsoil

5.3 Case study C — orphan historical fill left in place

One of the most challenging aspects of subsurface characterisation is to assess the condition/behaviour of what is referred to herein as 'orphan fill'. That is fill present on site for which there is no clear record of its genesis, thus the use of the term 'orphan'.

The pitfalls of trying to assess 'orphan' fill by means of post construction in situ density testing are presented in detail in Burman et al. (2008). This paper presents a series of examples and concludes:

> *'These examples represent a situation that is common in civil earthworks where fills have been apparently properly constructed by ostensibly competent civil contractors, with control testing by independent NATA registered geotechnical firms, under the overall supervision and approval of experienced, independent engineers. Yet, in each instance, retesting after completion has apparently produced compaction results below, and in some cases spectacularly below, the specified minimum achieved during construction.'*

In any case, often it is not the density that is at issue but the stiffness.

One successful approach is to use the larger diameter PLTs which can give an indication of the stiffness and strength (e.g. bearing capacity) of the upper 1.0 to 1.5 m of orphan fill and approve the appreciation of the underlying fill.

The following points present an example of characterising a thicker layer of orphan fill.

At a quarry site in Western Sydney which was being backfilled as part of its remediation, a more than 10 m thick layer of orphan fill was identified. The stiffness of the orphan fill was characterised as follows:

- One metre square steel settlement plates were placed at the top surface of the orphan fill, and for comparison purposes on the surface of adjacent controlled fill. The plates were grouted into place and surveyed at the four corners and at the centre. The plates were then buried with fill placed in accordance with the earthworks specification.
- Approximately two years later once the plates had been surcharged by approximately 7 to 15 m of fill, it was decided to drill back down to four of the settlement plates which had been buried. The purpose of drilling the boreholes was to locate and survey the level of settlement plates buried previously and thus assess the settlement of the plates and underlying fill due to the additional load imposed by the overlying fill. Three plates were located on orphan fill and one plate on controlled fill.
- Initial attempts at drilling the boreholes with hollow flight augering techniques was unsuccessful as the tungsten carbide drill bit refused at depths well above the plate depth. Subsequently percussion drilling techniques were used to drill the boreholes.

Table 1 combines the results of the settlement plate drilling with the information regarding the orphan fill thickness to estimate a notional constrained (one-dimensional) secant modulus of the orphan fill at the four locations.

Table 1 Summary of stiffness assessment from buried steel settlement plates

Measurements	Units	Settlement plates			
		PL1	PL2	PL3	PL4
Surface RL — September 2010	m AHD	52.2	51.71	56.47	55.55
Plate RL — October 2008	m AHD	43.11	44.00	41.30	41.24
Fill thickness above plate	m	9.09	7.71	15.17	14.31
Assumed fill unit weight	kN/m^3	20	20	20	20
Overburden stress	kPa	182	154	303	286
Plate RL — September 2010	m AHD	42.77	43.70	40.95	40.93
Calculated plate settlement	m	0.336	0.306	0.352	0.316
Assessed bedrock RL	m AHD	29.7	32.0	29.7	30.0
Fill thickness below plate	m	13.4	12.0	11.6	11.3
Fill type below plate	–	Orphan fill	Orphan fill	Controlled fill	Orphan fill
Average strain in fill below plate	–	2.51%	2.55%	3.02%	2.81%
Notional constrained (1D) secant modulus	MPa	7.3	6.0	10.0	10.2

The method allowed the stiffness of the orphan fill to be characterised as being between 60 and 100% of the controlled fill. The overlying earthworks were then designed accordingly.

5.4 Case study D — industrial sheds western and south western Sydney

Earthworks specifications have not changed significantly in the last 40 years. However, performance requirements relating to structures supported on the earthworks have.

An example of this is industrial sheds. The slab designers are requesting that the earthworks be designed to allow higher loads and limited deflections. The developers require the earthworks to essentially be cut fill balance (i.e. using site won materials) and the slabs to be as thin as possible.

Amongst other things, such as shrink swell movements, a key input is the stiffness that can be adopted at the slab subgrade level. Earthworks specifications that had been tried and tested to produce subgrades that were 'stiff enough' needed to be assessed in terms of the required performance.

The authors and their colleagues have for the last 10 years been doing this routinely by means of plate load testing. PLT is included in the specification as a direct measure of stiffness, in this case not substituting conventional compaction control but supplementing it to increase confidence in the actual performance of the conforming earthworks.

Some of the results of this testing have been previously published in Shen and Mostyn (2012). These results have been updated to include testing completed between 2012 and 2014 and are presented in Figure 6. The chart shows over 300 PLT results on four types of subgrade. It is noted that some of the clay/shale fill was stabilised with between 2 and 5% lime with the primary objective of increasing the California bearing ratio of the subgrade. Most of the tests were completed using a 500 mm plate diameter. The authors and colleagues have completed thousands of tests at other sites.

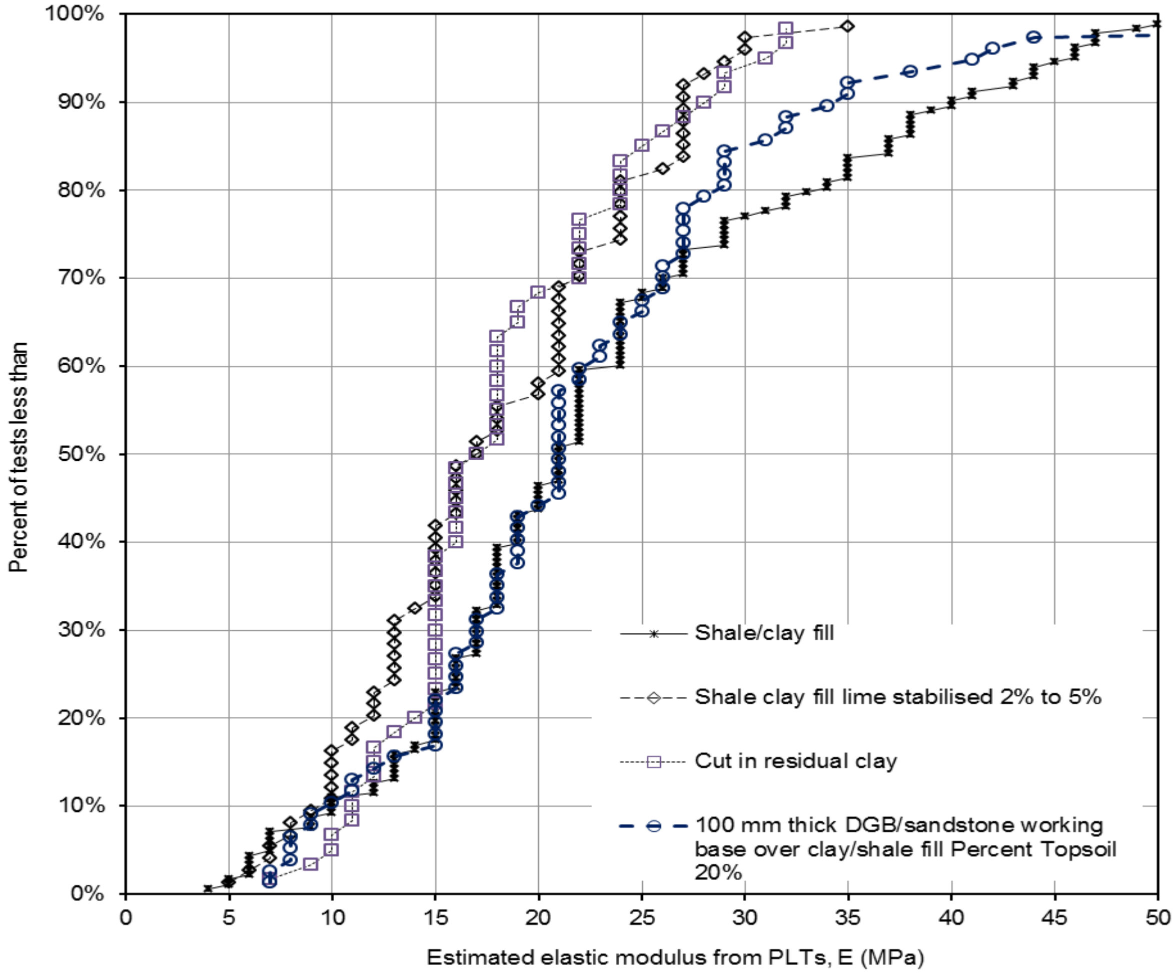

Figure 6 Summary of plate load test results on shale/clay fill in developments in western and south western Sydney

5.5 Case study E — concrete arch backfill

Table 2 presents the specification for backfill in the structural zone of a reinforced earth type structure comprising a reinforced concrete arch. The arch was required to support over 20 m of fill. The design of the arches relied heavily on the support provided by the backfill placed in the structural zone around the arch.

In these types of structures, the performance of the arch is heavily dependent on the stiffness (or in other words deformation response) of the backfill surrounding the arch.

The specification is a typical specification for backfill material which historically had resulted in adequate performance of the arches over a range of applications.

The authors were involved in one project where inadequate stiffness of the backfill resulted in excessive deformation of the arches and requirements for remediation of the arches.

Figure 7 presents a number of stiffness estimates for materials, some of which comply with the backfill specification, placed at various levels of compaction. These stiffnesses are based on published data. The stiffness presented is a secant modulus over the stress range between 0 kPa and the applied load. This is referred to as 'secant modulus from unstressed'.

The approximate stiffness used in the design was between 20 and 40 MPa. It is noted that the design actually adopted a Duncan Chang stiffness model that relates stiffness to confining stress. As can be seen from Figure 7, there are a large number of material which would not result in the design stiffness even at the specified compaction values.

Table 2 Summary of specification requirements for arch backfill

Item	Requirement
Unsuitable material	Capable of being compacted in accordance with the specified requirements to form a stable mass of fill. Free from organic or other deleterious material.
Grading	Selected granular material with 100% smaller than 100 mm, no more than 15% passing the 75 µm sieve, and a CU ≥ 2.
Compaction	Density ratio between 95 and 100% of SMDD.
Moisture	The placed moisture variation between 0 and 2% dry.
Compaction plant	Compaction equipment not exceeding 8 tonne static weight; vibration not permitted.
Placement	Backfill is to be placed in maximum uniform compacted layer thickness of 375 mm evenly along the length of the arch structure.
Testing — material	A report containing test results for all material proposed to be used must be submitted to the Client for approval prior to the commencement of construction and prior to changing the source of the selected fill. A copy of this report is to be forwarded to the designer for review prior to any construction commencement.
Testing — density	Conduct density tests at sufficient frequency and location to ensure that all the backfill has been uniformly compacted to the specified compaction. As a minimum, the requirements of AS3798 should apply (Standards Australia 2007).

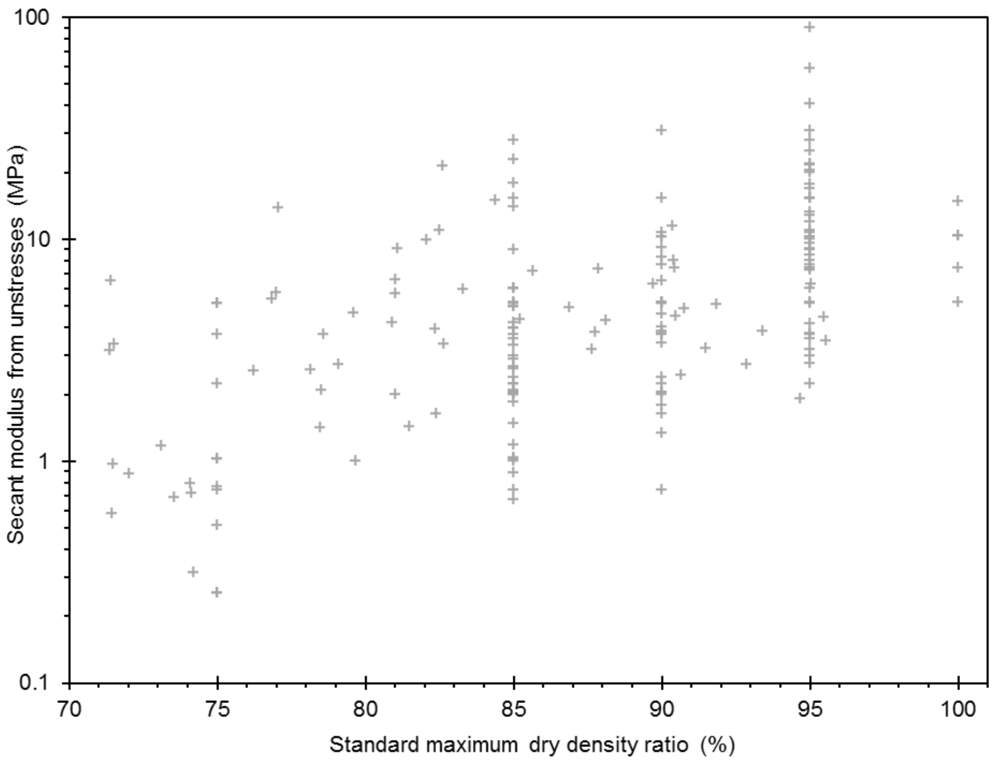

Figure 7 Modulus estimates provided in the literature for a range of materials at various densities (Howard 1977; 2006; McGrath 1998; Selig 1990; Highways Agency and BRE 2007; Standards Australia 1998)

Figure 8 presents a summary of recommended stiffnesses from literature (NHCRP and AS2566.1) and measured stiffnesses (from large-scale oedometer tests) for material which actually complies with the specification requirements at various placement densities.

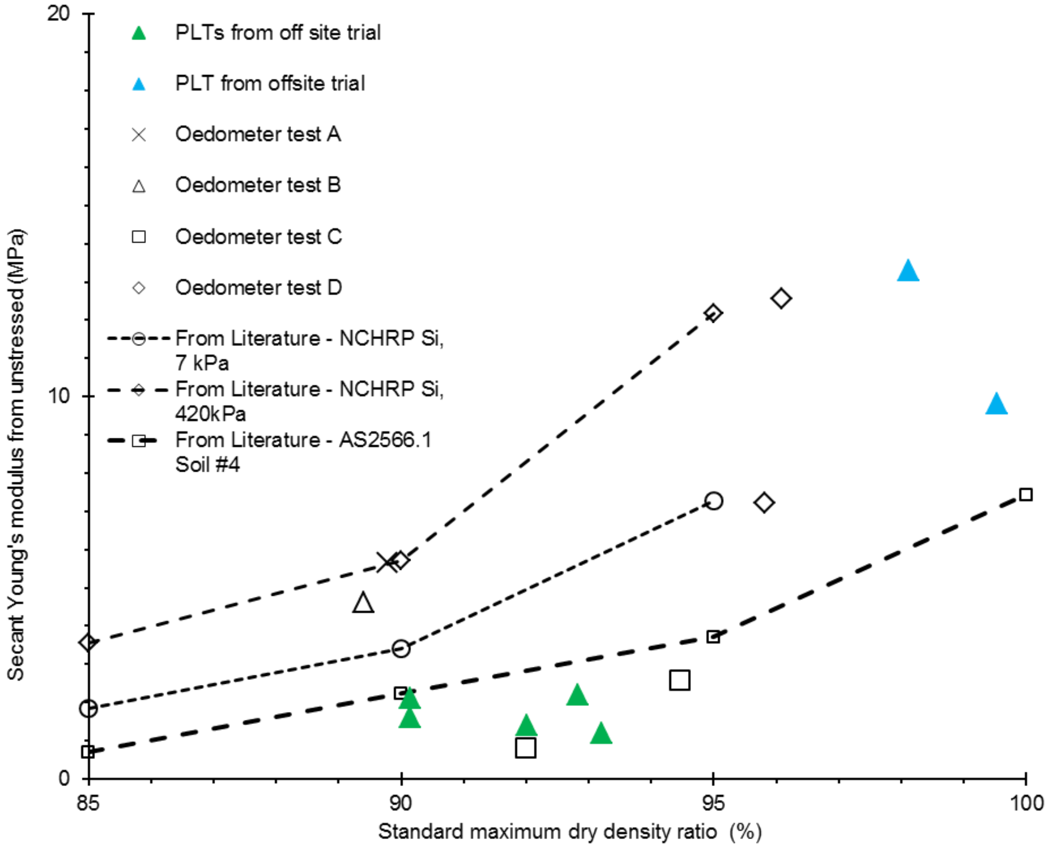

Figure 8 Modulus estimates provided in the literature and lab testing for complying materials

As part of investigating the causes of the deformations, a field trial was undertaken which allowed plate load testing of the actual material used in the backfill placed as per the requirements of the specification using the equipment available during the construction works. It is important to note that the compaction had to be undertaken using small plant (due to access constraints) with no vibration (as per the specification requirements).

The results of the plate load testing in terms of stiffness estimates are presented as triangles on Figure 8. As can be seen it is likely that had the specification required, even some, direct measurement of the stiffness, the designer would have become aware that the specification as implemented by the contractor was resulting in significantly lower stiffness than required by the design, and even than could be expected for most complying materials.

In this application, the inadequate stiffness of the backfill had significant implications on the structural performance. It is the authors' opinion that direct measurement of stiffness during the works would have identified the inadequate stiffness of the backfill.

5.6 Case study F — deformation behaviour of a buried polypropylene tank

The authors were involved on a project where it was required to assess/predict the short-term and long-term response to loading of a buried polypropylene tank. The polymer tanks rely on ground support around their perimeter as part of the design. Furthermore, the tanks rely on the overlying fill material to spread the load applied on the tanks.

In order to assess the long term response to loading, a large-scale loading test was planned and executed which involved loading a 6 × 6 m area with two layers of brick pallets applying total pressure of 32 kPa (refer to Figure 3). Precise surveying was then used to measure settlement during and post application of the load. This allowed the measurement of the 'system' stiffness rather than breaking the system down to individual components e.g. tank response, subgrade response, overlying fill response and estimating the stiffness of each element by indirect measurements/descriptions. A schematic of the test and measured deflections are presented in Figure 9.

It is another example of where direct measurement of stiffness removed significant uncertainty with regards to deformation behaviour.

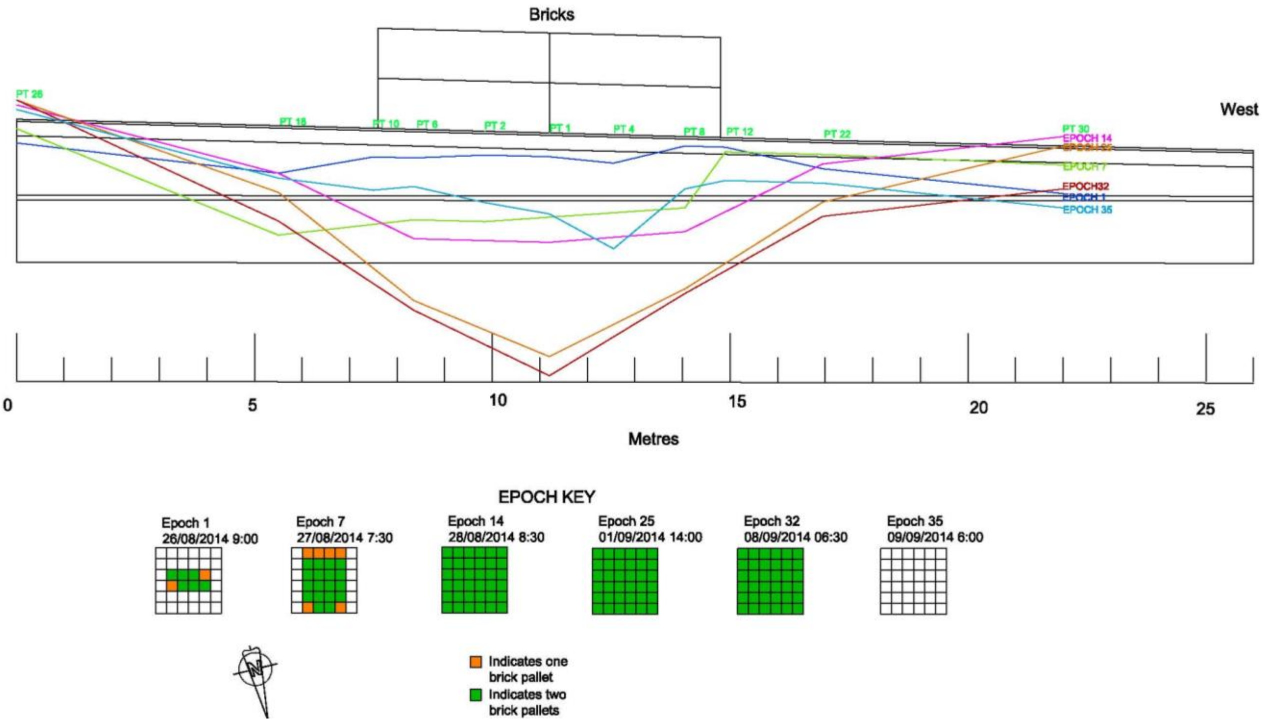

Figure 9 Schematic of load test and measured deflection (not to scale)

6 Conclusion

Measuring stiffness of earthworks is possible and at times provides significant benefits to a project.

Acknowledgement

The authors acknowledge their colleagues at PSM, as their efforts underpin much of the work presented in the above case studies.

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