Performance based testing of earthworks using MASW, Geogauge and Bender Element techniques

Basé sur la performance test du terrassement en utilisant de techniques MASW, Geogauge et élément Bender

Bindumadhava Aery, Adam Kemp, James Davis
Transport, Aurecon, Australia, Bindumadhava.Aery@aurecongroup.com

ABSTRACT: The performance of compacted earthfill is traditionally assessed based on an in situ determination of the dry density and moisture content using a nuclear densometer gauge. Achievement of the specified density ratio provides the engineer with an indirect confirmation that the stiffness of the earthfill is satisfactory, but rarely are these values measured directly, even when the stiffness may be a governing factor in the design of the earthworks. With recent advances in laboratory and field measurement of the small strain stiffness of geomaterials, using techniques such as bender element triaxial testing, Geogauge, and multi-chanel analysis of surface waves, there are now convenient and repeatable methods of directly assessing the stiffness of recently compacted earthfill materials. This paper presents a case study where combinations of Geogauge, MASW and Bender Element testing have been used to evaluate the stiffness of recently compacted earthfill bunds. In this study the stiffness of the compacted fill has been a governing criterion for the final use of the earthworks. The methods have been compared with the results from conventional Nuclear Densometer Gauge (NDG) testing and recommendations provided for the future use of in situ stiffness measurement in earthworks applications.

RÉSUMÉ : La **performance** de remblai compacté est traditionnellement évaluée selon une détermination in situ de la teneur de la densité et l'humidité sèche à l'aide d'une jauge de densometer nucléaire. Réalisation du rapport de densité spécifié fournit l'ingénieur avec une confirmation indirecte que la rigidité du remblai est satisfaisante, mais rarement sont ces valeurs mesurées directement, même lorsque la rigidité peut être un facteur régissant dans la conception des terrassements. Avec les progrès récents en laboratoire et au mesure de champ de la raideur de petite déformation des géomatériaux, utilisant des techniques comme l'élément bender essais triaxiaux, Geogauge et analyse multi-chanel des ondes de surface, il y a maintenant des méthodes reproductibles et pratiques de l'évaluation directe de la rigidité de remblai compacté récemment. Cet article présente une étude de cas où les combinaisons de Geogauge, MASW et bender élément stable ont été utilisées pour évaluer la rigidité des diguettes en terre compactée récemment. Dans cette étude, la rigidité du remblai compacté a été un critère régissant l'usage final des terrassements. Les méthodes ont été comparés avec les résultats des densometer nucléaire conventionnel jauge tests et recommandations fournies pour l'utilisation future de la mesure de rigidité insitu dans les demandes de travaux de terrassement.

KEYWORDS: Earthworks, compacted fill, stiffness, MSAW, Nuclear Densometer, Geogauge, Bender element test,

1 INTRODUCTION

Earthworks is often the predominant part of infrastructure projects. Large quantity of naturally and locally available soil being used as fill material to form structural fill. Compaction control of the fill is based on layer thickness and relative dry density. It is difficult to consider uniform geotechnical parameters for design purposes as the engineering behaviour of structural fill is depended on basic fill material properties, moisture content and relative density.

Compaction conditions and post-compaction variations in degree of saturation affect the properties and behaviour of compacted cohesive soils. The effects of these conditions on static properties and response of these soils have been studied extensively (Fredlund and Rahardjo 1993; Brown 1996).

The geotechnical design of structural fill supporting sensitive structures are based on serviceability requirements to ensure the performance of the structure, in other words deformation behaviour of the fill material governs the design. The realistic prediction of ground movement (deformation behaviour) requires a sound knowledge of ground stiffness and its stress stain behaviour (Deighton, 2016).

While the simple and traditional investigation techniques typically employed generally permit the ground profile and strength to be estimated with reasonable accuracy. Direct assessment of ground stiffness is rarely attempted due to the numerous difficulties accessing the structural fill with suitable in situ testing or high quality sampling equipment. As a result, ground stiffness values are often determined from simple empirical relationships with basic in situ measurement of undrained strength or determination of in situ dry density. For sensitive structures founded on structural fill it is essential to determine the stiffness more accurately using direct measurement to ensure the design intent.

In some instances, an understanding of the conformance of the compacted fill is required, which was built for a specified relative density. It is not practical to verify the dry density of the compacted fill at different depths with conventional sand replacement or nuclear densometer gauge methods.

With recent advances in laboratory and field measurement of the small strain stiffness of geomaterials using techniques such as bender element tranducers, Geogauge, and Multi-channel Analysis of Surface Waves (MASW), there are now convenient and repeatable methods of directly assessing the stiffness of both old and recently compacted earthfill materials. These methods also offer the advantage of providing a larger quantity of assessable data which can assist in identifying and rectifying areas of poor or non-conforming compaction during construction.

2 BACKGROUND

One of the most critical earthworks components for a infrastructure project, located in southeast Queensland, Australia was the construction of a approximately 1200m long earthfill bund and concrete rail beam to support a travelling coal stacker system. The coal stacker system is settlement sensitive and therefore good quality control on the placement and compaction of earthfill materials is required.

Construction of the bund had reached the design crest level and the concrete rail beam poured in several locations and no non-conformance reports (NCRs) had been raised based on the results of the contractors quality control (QC) testing. However, following field inspections revealed that the approximately 30% of the fill layers, predominantly in the upper 2 metres of the embankment, exhibited stony horizons of significantly non uniform moisture content, inadequate mixing of gradation and low density. But these inspections were in contradiction to the results of the QC testing.

The irregularities in the bund construction were only realised once trimming of the batter slopes occurred. Therefore, the majority of the bund had been constructed and removal and reconstruction of the non-conforming fill section, along with the concrete rail beams (1m x 0.6m) and reinforced granular base. This was found to be expensive as a 3 month delay to the project's critical path occurred.

In addition to the project related issues, the problem was further compounded by the fact that the Contractor's QC records indicated that the bund construction was as per the project specification, yet visual observations contradicted the QC testing.

While keeping the above factors in mind, a team of geotechnical, structural and civil engineers recognised that either simply accepting the QC results or assessing the bund integrity using normal means (density testing, boreholes or DCPs) would not be sufficient given the importance and sensitivity of the gantry stacker to the terminal's operation

3 DEVELOPMENT AND EXCECUTION OF AN INNOVATIVE TESTING SOLUTION

It was recognised that low density zones and non-uniform compaction in the upper 2m of the bund could lead to future issues with the load-settlement performance of the coal stacker, which may adversely affect the intended stacker performance. Considering cost and time, it was decided to examine, what in situ testing would be necessary to provide greater certainty on the future performance of the bund.

To develop a suitable testing plan it is important that the uniformity of the bund fill stiffness was of the upmost importance to understanding the load-settlement performance of the rail beams. Conversely, it was also highlighted that stiffness was not a specification requirement, rather a result of meeting the compaction specification. The compaction specification was to be checked using the typical nuclear densometer gauge (NDG) form of testing. Therefore, to achieve the competing aims of assessing the stiffness of the bund fill material and measuring conformance with the specification, a two-fold approach to the testing was required.

To assess the stiffness, the first phase of testing includes undertaking the MASW testing along the full alignment of the completed bund. The aim of the MASW testing was twofold, firstly to identify zones of poor compaction based on changes in shear wave velocity and secondly to provide an estimate of the in situ stiffness of the compacted bund material for further analysis.

To ensure that there was a link between the MASW testing and specification, bender element testing is required on laboratory prepared samples of the compacted bund fill material. Researches indicated (Heitor et al, 2012) that the bender element testing would provide a reference shear wave velocity for a material that is compacted within the specification requirements in the laboratory while the MASW would provide an estimate of the field conditions. This hypothesis is similar to the methodology used for nuclear densometer gauge testing, however, the advantage of the method that we proposed was that the engineering parameter that is of most interest to the designer is directly measured, rather than indirectly estimated.

3 .1 *Bender element testing*

Bender element testing is a non-destructive laboratory test method used to investigate the small strain behaviour of soils and rocks. This method uses standard triaxial apparatus and generates and detects shear and compressional waves passing through the sample. From the shear wave velocity, the small strain modulus (G_0) can be evaluated using the principles of elastic theory,

$$G_0 = \frac{\gamma}{g} Vs^2$$

where, ɣ is the bulk unit weight (kN/m3), g is the gravity acceleration (m/s2) and Vs is the shear wave velocity (m/s). Similarly, from the compressional wave velocity, the small strain constrained modulus, M_0 can be evaluated by

$$M_0 = \frac{\gamma}{g} Vp^2$$

Two representative soil samples were selected from the site for laboratory testing. Each sample was compacted to the required specification minimum compaction level (95% MDD Std) at two different moisture contents; -2%OMC and +2%OMC. The testing aimed to provide a lower bound estimate of the material stiffness (shear wave velocity) based on the specification limits.

A bender element test was undertaken on each sample. Because the shear wave velocity increases with increased overburden (confining pressure), the samples were tested with no confining pressure. The results of this testing can therefore be considered representative of materials found at the surface of the bund and also a conservative lower bound for shear wave velocity for material deeper within the bund. The results of the bender element testing are presented in Table 1.

Table 1 Summary of Bender element test

Specimen	*Vs (ms)*	*Vp (ms)*	*G_0 (MPa)*	*M_0 (MPa)*
w= 23.5% (OMC -2%) γ_d = 13.41kN/m^3 (95% $\gamma_{d\ max}$)	**231.1**	**405.4**	**90.1**	**279.9**
w= 27.6% (OMC +2%) γ_d = 13.45kN/m^3 (95% $\gamma_{d\ max}$)	**207.5**	**391.1**	**75.3**	**267.4**

Table 1 shows the shear wave velocity to vary from 207m/s to 231m/s for samples compacted at +2%OMC and -2%OMC respectively. The lower bound shear wave velocity therefore occurs when the materials are compacted wet of optimum.

As shown in Figure 1, the range of results are supported by other studies by Heitor et al (2012) which show that there is a distinctive drop in shear wave velocity between materials dry and wet of optimum.

The MASW method is a non-destructive seismic method which uses the elastic properties of subsurface materials to determine subsurface structure. By analysis of the dispersive properties of varying frequencies from a single seismic source, shear-wave velocity (Vs) and associated geotechnical parameters can be determined.

In the MASW method, the subsurface shear wave velocity distribution can be developed from the analysis of the dispersion and numerical inversion of the seismic data, produced by a surface impact source and recorded on standard, digital multi-channel seismographs (Heitor et al, 2012).

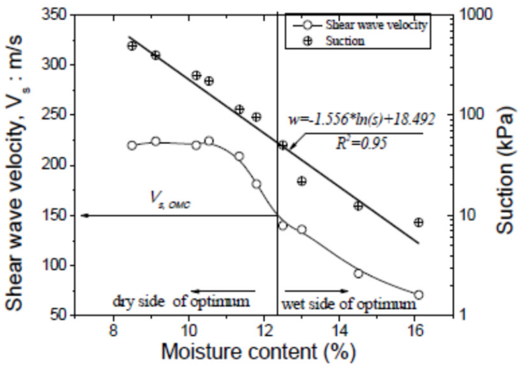

Figure 1 Shear wave velocity relationship vs moisture content.

3 .1 *MASW Seismic Survey*

The MASW seismic survey was undertaken by Earthsolve. Seven survey lines were tested along the full length of the Stacker Bund using the MASW method. The geophone spacing for the survey was 1m, intial offset, -5m, 0m and +5m and a record length of 18m. Analysis of the dispersion characteristics of the seismic surface waves and inversion of the dispersion curve to S-wave velocity was undertaken every 4 to 6m to provide a 2D profile. Figure 2 presents longitudinal sections of the calculated shear wave velocity versus depth below surface level along the length of the bund. The depth of investigation was approximately 10m.

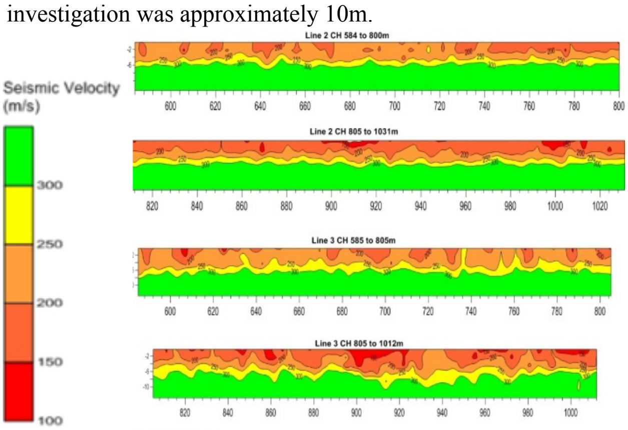

Figure 2 - Results of the MASW testing (dark red showing areas of poor compaction)

The MASW results indicate that the material generally increases in shear wave velocity with depth. However, it should also be noted that there is typically a natural increase in material stiffness with depth due to the increasing overburden pressure. The majority of low velocity zones (less than 150m/s) tender to occur in the upper 2m of the bund. Two deeper zones of low velocity occur between CH900 and CH920.

3.2 *Geogauge testing*

The Geogauge (Soil Stiffness Gauge) is a portable stiffness testing device that was carried out in parallel to the MASW survey and test pit and NDG investigation. The Geogauge measures the stiffness of materials from the surface to a depth of approximately 0.15m. The Geogauge was used to correlate against both the MASW and NDG testing at the bund crest level and in the test pits respectively. The primary purpose of the Geogauge testing was to provide modulus of subgrade reaction values for the assessment of the rail beam, if non-conforming fill materials were found.

Statisical analysis indicates the median Geogauge reading for the bund is 14MN/m the coefficient of variation for these readings is 36%. The variation in the Geogauge reading is significantly higher than the NDG. The design modulus of subgrade reaction correlates to a Geogauge reading of approximately 12MN/m. The results show that over 30% of values are less than the assumed design value. The low Geogauge readings between CH120 and CH230 correlated with the MASW results; however, because the testing was undertaken along the same line, they would also be affected by the stress relaxation of the eastern slope and the blinding layer below the bund surface. The locations of low stiffness between CH900 and CH1000 correlate with the NDG results.

4 IDENTIFICATION OF POTENTIAL NON-CONFORMING ZONES

The results of the laboratory and MASW testing were used to identify zones that potentially do not meet the specified compaction requirement. This was achieved by comparing the reference shear wave velocity, 207m/s, determined from the bender element testing to a normalised field value determined using the MASW. Shear wave velocities between 150m/s and 200m/s were still found to be critical below 1m depth and were nominated for further testing.

Test pit and Nuclear densometer gauge (NDG) testing were undertaken at selected low locations depths to validate the observed low shear wave velocity (low density). While undertaking the test pitting and NDG testing, Further stiffness testing using a Geogauge were carried out. The Geogauge was used adjacent to each of the NDG tests to correlate and compare against the NDG and MASW testing.

The testing regime identified seven locations, totalling over 210m of the bund alignment, which had material which had not been compacted to the project's specification. The NDG results have been reviewed against the MASW data (Figure 3).

The comparison in Figure 3 shows that along Line 3 there is a good correlation between the zones of low shear wave velocity picked up by the MASW and the DDR results that do not meet compaction specification. Furthermore, the zone of low shear wave velocity that extends across the bund between Line 2 and 3 at CH320 (bund CH900) has been corroborated by the NDG testing. This correlation confirms that the zones identified by the MASW along Line 2 and 3, with shear wave velocities less than 200m/s, need further assessment and potentially rectification.

5 REVIEW OF BUND PERFORMNCE

Several of the non-conforming locations were located adjacent to previously cast concrete rail beams and therefore there was concern from the client on how removal of these beams would impact the project schedule. Therefore, futher study has undertaken to how the rail beam would behave if the material was to be left in place or alternatively what ground improvement could be undertaken to improve the bund performance.

To answer this question the MASW and Geogauge testing results were used to determine a small strain modulus. The small strain modulus determined by these methods was factored by 0.2 to a working-strain modulus based on the estimate strain imparted by the rail beam and the stiffness degradation curve proposed by Vardenga and Bolton (2011) for fine grained materials. The result of this assessment were input into a finite element analysis program for assessment. The analysis showed that at several locations, totalling less than 100m of the original 210m, the future elastic settlements were going to be excessive and stiffening was required. In other locations the analysis showed that no stiffening was required and the bund fill material could be left as is. This analysis and subsequent reduction in rectification requirements clearly showed the benefits of directly measuring stiffness for earth bund construction rather than simply using the standard density testing. Monitoring during commissioning of the coal stacker confirmed the elastic settlement and adequacy of these areas.

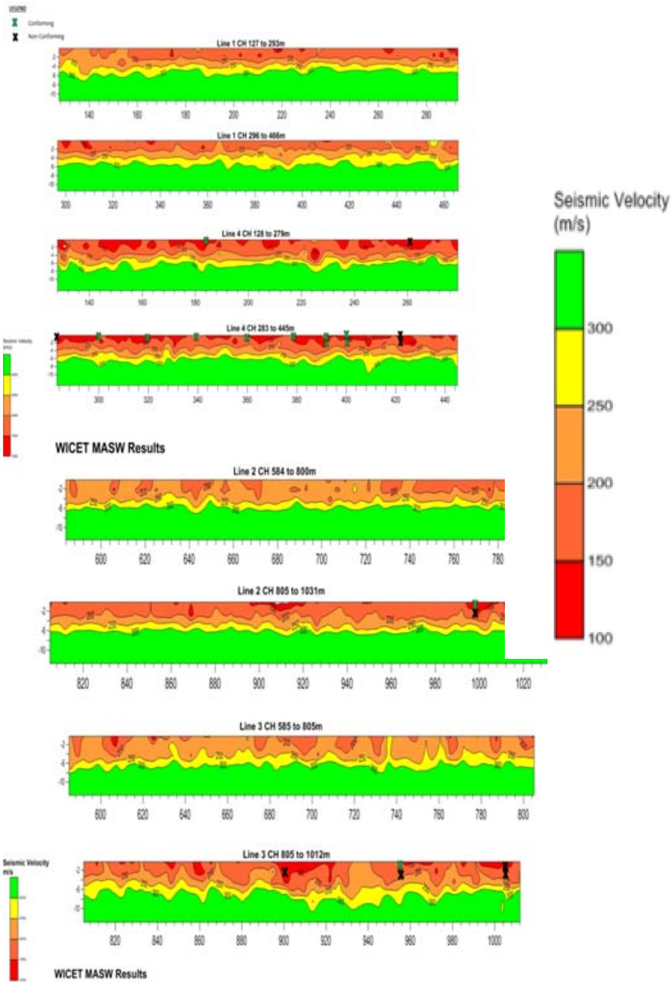

Figure 3 – Comparison between MASW and Nuclear Densometer gauge

.

6 CONCLUSIONS

Conventional NDG testing is used throughout the construction industry to confirm the compaction standard of earthfill materials. Although widely used and easily understood, this form of testing does not provide the designer with a direct measurement of the fundamental properties (stiffness and strength) that govern the earthfills performance. In this case, the designer developed a cutting edge approach, using MASW, Bender Element and Geogauge testing to directly measure these fundamental properties, on a settlement sensitive gantry stacker bund, while still checking conformance with the project's specification. This approach allowed concerns over the extent of poorly compacted material to be quickly and confidently identified, while the direct measurement of stiffness resulted in a significantly smaller section of the bund requiring rectification. The result for the client was a significant saving in the cost of rectification (compared to complete removal and replacement) and more importantly limiting potential delays of the project's critical path. The testing approach also raised questions as to the quality of the field density testing employed by the Contractor, or by the industry as a whole.

This project has also highlighted that seismic testing can offer significant advantages over conventional methods in terms of quality, quantity and speed of data collection. The speed of data collection would limit the amount of time a tester would need to be one site and also the use of seismic testing in lieu of NDG would also limit safety concerns over the exposure of testing staff to radiation.

Further use of these methods on other projects that we undertake can potentially lead to significant time and cost savings for our clients.

7 ACKNOWLEDGEMENTS

Authors wish to thank Aurecon colleagues for their support during investigation and preparation of this paper.

8 REFERENCES

Brown, R. W., 1996, Practical Foundation Engineering Hand-book, McGraw-Hill, New York, NY.

Deighton M, 2016, Improved stiffness of ground stiffness for railway projects using continuous surface wave testing, Ground Engineering, November 2016.

Fredlund, D. G. and Rahardjo, H., 1993, Soil Mechanics for Un-saturated Soils, John Wiley & Sons, New York, NY.

Heitor, A., Indraratna, B. and Rujikiatkamjorn, C. (2012). Characterising compacted soil using shear wave velocity and matric suction. Australian Geomechanics Journal, 47 (2), 79-86

Vardenga, P. J. and Bolton, M.D. (2011). Practical methods to estimate the non-linear shear stiffness of fine grained materials. International Symposium on Deformation Characteristics of Geomaterials, September 1~3, 2011, Seoul, Korea, 372-379