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An application of lightweight portable impulse and variable energy dynamic penetrometer devices for compliance testing of performance-based rail formation

Une nouvelle méthode d'essai de conformité des sols pour des travaux de terrassement des couches de forme utilisant le pénétromètre dynamique à énergie variable et l'essai à la plaque dynamique allemande

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ABSTRACT: Alternative compliance testing methods for earthworks have been covered in many recent publications. One key aspect of alternative compliance testing is that it supplies parameters that correlate directly to design, rather than index tests which have an additional level of correlation and error margin. For example, laboratory CBR testing is a time-consuming test with a significant correlation error with design parameters, particularly in cohesive materials in a semi-arid environment. Performance-based formation design is a requirement for many Australian projects, including the Inland Rail (IR) project and finds many applications within operation and maintenance. Rail formation performance-based mechanistic design allows a balance between capital expenditure (CapEx) and asset operation/maintenance (Opex) by providing an indication of the formation performance with rail traffic forecast. This performance is expressed in terms of deformation governed by strength and stiffness. Resilient modulus and compressive strength are critical soil input parameters for mechanistic design and the estimation of deformation over time. These parameters can be tested directly using alternative compliance testing methods. This paper presents the results of compressive strength and resilient modulus measured in situ using a Variable Energy Dynamic Penetrometer (VEDP), Light Weight Deflectometer - Portable Impulse (LWD-PI), and Plate Load Test (PLT) and laboratory Unconfined Compressive Strength (UCS) during a full-scale trial. This paper also presents an alternative compliance testing method for a brownfield application. A geospatial/cloud based report displaying near real-time communication of the alternative compliance results is presented. The alternative tests reduce the level of laboratory testing effort while the near real time display of results aids in construction time frames which is of particular benefit to projects in remote locations. The methods can be combined with traditional field testing methods to develop site-specific correlations and validate geotechnical parameters assumed in the design.

RÉSUMÉ: De nouvelles méthodes d'essai de conformité des sols à des spécifications propres aux travaux de terrassement des couches de forme ont été récemment présentées dans plusieurs revues professionnelles. Leur originalité est de fournir des mesures directement liées aux paramètres de dimensionnement plutôt que devoir compter sur des indices laboratoire et leur corrélation qui sont limitées comme par exemple avec le test CBR en laboratoire, qui demande du temps et des contraintes de mise en œuvre avec une marge d'incertitude qui peut devenir significative pour des sols argileux dans un environnement semi-aride. La conception basée sur la performance de la sous-couche et la plateforme est une exigence pour de nombreux projets australiens, y compris le projet Inland Rail (IR) et trouve de nombreuses applications dans l'exploitation et la maintenance. Cette méthode de conception permet de suivre un équilibre entre les immobilisations et les coûts d'exploitation et de maintenance en fonction du trafic prévisionnel. Cette performance de la sous-couche et de la plateforme s'évalue selon les déformations calculées en fonction de la résistance et la rigidité des matériaux ainsi que les effets dus à la circulation des trains. La rigidité et la résistance à la compression sont les paramètres critiques de mécanique des sols de cette méthode qui permet de prévoir l'évolution et les déformations dans le temps. Ce sont ces paramètres dont la conformité peut être testée avec des méthodes alternatives. Cet article présente les résultats des mesures de rigidité et de résistance à la compression, réalisées in situ selon les méthodes de sonde de battage, essai de charge sur plaque, essai à la plaque dynamique allemande (LWD-PI) et essai (en laboratoire) de résistance en compression (UCS) au cours d'une campagne de tests en grandeur nature. Une méthode alternative d'évaluation de la conformité des terrassements est présentée dans cette étude. Cette méthode utilise les coordonnées géospatiale des tests permet de visualiser les résultats quasiment en temps réel et se révèle particulièrement avantageuse dans un environnement de chantier. Elle réduit significativement le nombre de tests à effectuer en laboratoire, ce qui est particulièrement appréciable dans des sites éloignés de tout. Ces méthodes peuvent être combinées avec des méthodes traditionnelles de contrôle de conformité pour évaluer des données spécifiques au site et valider les paramètres géotechniques pris en compte lors de la conception.

KEYWORDS: Rail formation design; Variable Energy Dynamic Penetrometer; Portable Impulse, earthworks compliance testing.

1 INTRODUCTION

Performance-based formation design is increasingly in demand as it allows for balancing Capital Expenditure (CapEx) and Operating Expenditure (OpEx) by developing predictive maintenance. Prediction of rail formation performance with rail traffic tonnage is governed by the strength and stiffness of rail formation and subgrade within the zone of influence of rail.

Traditional earthworks compliance testing generally relies on Index tests, California Bearing Ratio (CBR), and compaction testing. Such test regimes are generally suitable for imported and quality controlled earthworks materials, where assigned values can be established. The heterogeneity of site won earthworks materials makes assigning values challenging, resulting in time-consuming CBR and compaction testing with associated correlation error in design parameters.

Reducing environmental impact by limiting the importation of large amounts of material (and disposing of surplus) together with improving project sustainability, often requires maximising re-use of site-won materials. For brownfield rail projects, this includes material within the rail formation which varies naturally through the life cycle of the asset due to live traffic, repairs, flood and other climatic factors and weather events experienced onsite .

Typically, the purpose of alternative compliance testing is to:

(1) Reduce the time lag between placement of material and compliance test results.

(2) Supply parameters that correlate directly with design.

(3) Reduce intrusive testing.

The alternative compliance testing can complement or be used to reduce traditional compaction testing.

The alternative compliance testing methodology presented in this paper was developed based on a series of trials for the Narrabri to North Star (N2NS) section of the Inland Rail program. The driver for developing an alternative compliance test was to test parameters directly correlating to the strength and stiffness assumed in the design while maintaining 100% brownfield material reuse to reduce the environmental impact associated with importing a large quantity of material. The test results measured are all georeferenced, allowing rapid reporting.

2 TRADITIONAL APPROACH TO MATERIAL CHARACTERISATION AND COMPACTION COMPLIANCE TESTING METHODOLOGY AND DISCUSSION

2.1 *Characterisation of fill material prior to construction*

The characterisation of imported quarried material can be completed in a controlled environment (due to consistent excavation and processing techniques), and thus the testing frequency and material quality of imported fill materials can be continually monitored.

In comparison, although the soil strength and stiffness of site won materials can be characterised during site investigation the inherent variability within existing material units and adopted excavation processes makes achieving a uniform fill material challenging, especially in brownfield conditions.

Variability present within rail corridor site won materials may also impact the construction schedule due to the time lag between excavation / re-useof the material and receipt of test results .

The following comments are made regarding traditional material geotechnical performance testing:

(1) Sample preparation to replicate long term field behaviour for Triaxial testing, CBR and Unconfined Compressive Strength (UCS) for stabilised soil is challenging. (Further details are presented in Section 3).

(2) CBR testing results for cohesive material are highly variable with low repeatability. The results are also governed by soaking duration (traditionally soaked for four days) which is unlikely to represent the long-term behaviour of both fill and in situ materials in the field, particularly in the context of rail formation in a semi-arid environment.

In addition to the sampling and testing limitations, empirical correlations are widely used in the industry to develop geotechnical design parameters from CBR and index tests. The geotechnical parameters from the correlation are increasingly used in Finite Element and Finite Difference geotechnical packages, with the expectation of a high degree of accuracy in predicting deformation - for example in the order of a few millimetres for transient rail deflection. The variability inherent in the empirical correlations means that the margin of error often exceeds the magnitude of the predicted deformations resulting in an unrealistic expectation of accuracy.

2.2 *Compaction testing of fill material during construction*

Current specifications frequently adopt assessment of the achieved compaction of fill via the use of a nuclear moisture-density gauge, which measures density and moisture.

Such tests require a compaction curve performed in a laboratory to calculate the relative density and moisture ratio. An assigned value (from compaction curve) is feasible for homogeneous material (quarried and processed material such as capping or structural fill) and can save time.

The challenge in brownfield conditions is the inherent variability of site won material, which prevents the establishment of assigned values and leads to a time lag between completing nuclear moisture-density gauge field readings and assessment of relative density and moisture ratio (which requires an associated laboratory compaction curve to be constructed). Compaction test results can take anything from 2 days to several weeks, making quality assurance difficult and increasing the risk of re-work. Further, the compaction effort and layer thickness for sample construction in the laboratory may not be directly compatible with the compaction effort applied in the field, especially if heavy and / or dynamic compaction equipment is utilised.

Compaction testing using a nuclear moisture-density gauge is also limited to the layer thickness tested, typically 300mm.

2.3 *Traditional strength and stiffness testing in brownfield during construction*

Traditionally, strength and stiffness parameters are verified during construction through index testing; CBR, PLT (less frequent) and UCS for the evaluation of stabilised soil. CBR and UCS are laboratory based tests with similar limitations to those discussed previously.

The direct measurement of strength and stiffness from a PLT is rarely carried out as part of compliance testing regimes. A PLT requires specialist equipment and plant to apply the reaction load, is time consuming and is thus often considered impractical for routine use within a construction environment.

While UCS testing for a stabilised soil is a direct measurement it is often carried out on reconstituted sample. This may result in the tested sample being unrepresentative of the insitu material condition (e.g. due to removal of gravel sized particles, compaction effort applied and moisture content used). Such testing is also time consuming, with several days (sometimes weeks) required for the completion of one test due to sample preparation and curing timeframes. Similar constraints apply to CBR and tri-axial testing.

Although Index testing is faster, the margin of error associated in its correlation to strength / stiffness remain as discussed in Section 2.1.

3 EARTHWORKS PROJECT APPLICATION

3.1 *Context*

The N2NS project is part of the Inland Rail program and located in northwest New South Wales. The project starts north of Narrabri Junction and terminates at North Star approximately 186 km north, and comprises an upgrade of the existing rail track.

The project facilitates heavier trainloads (up to 30 Tonne Axle Load, TAL), increased train speeds (80 km/hr), increased traffic frequency and tonnage through the design life (50 years).

The site's terrain is gently undulating, with the alignment crossing several broad floodplains, overland flow paths and smaller creeks. Numerous existing culverts and low clearance bridge locations are generally associated with these geomorphic features. Existing rail embankments are generally of limited vertical height (0.5 m to 1.5 m) and were constructed from soil won from the track's cess drain. Black soils (highly reactive soils) often exhibiting gilgai geomorphic features are known to exist

along the N2NS alignment.

The existing rail formation comprised ballast, heavily fouled ballast, and ash. The subgrade comprised firm to stiff clays ranging in undrained shear strength (*Su*) from 50 to 60kPa. The subgrade was noticeably wetter directly under the existing formation. Numerous mud holes, ballast pockets, and washout repairs were observed within the existing formation.

As part of the project's site characterisation, over 300 test pits were excavated within the existing formation between September and October 2017 (from shoulder to shoulder). A typical "w" shaped feature was noted on the majority of the test pits as illustrated in Figures 1 and 2; evidence of progressive shear failure mechanisms well described in the literature (Li et al. 2016).

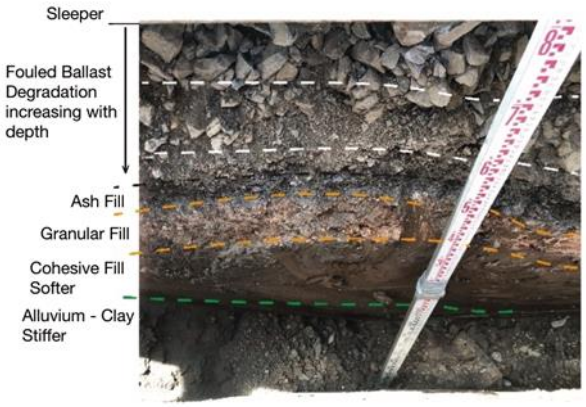

Figure 1. Typical soil profile (perpendicular to existing track alignment) recorded during N2NS geotechnical investigation showing typical 'w' shaped (orange dash), ash and progressive ballast degradation.

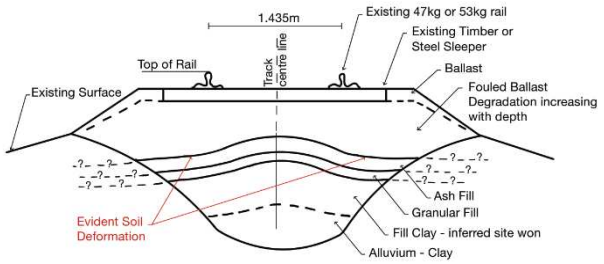

Figure 2. Typical test pits for the N2NS geotechnical investigation.

Furthermore, Figure 1 and Figure 3 illustrate the three-dimensional complex behaviour taking place within the formation (as further discussed in Blanchet & Yang, 2021). The excavation face seen on Figure 3, was located approximately at the centerline of the pre-existing track, and shows the significant deformation of both natural and imported soils below the sleeper footprints. The ash layer is pale grey, overlaid by the degraded ballast (darker grey). This also shows fill degradation over time, combined with an ingress of moisture.

Figure 3. Photo showing typical plastic deformation of rail formation behavior during N2NS earthworks trial.

Based on laboratory test results (refer Blanchet & Yang, 2021) it was interpreted that the existing formation is at an equilibrium moisture content (*Sr* around 80%) and is generally much wetter than typical ground conditions observed offset from the existing embankment. This is a typical feature of existing rail formations built upon a clay subgrade in a semi-arid environment, and has been noted by personal observation of the authors at several sites in Australia, all within semi-arid environments (e.g. Mount Isa – Cloncurry Central Queensland, Tom Price Line – Western Australia, Parkes to Narromine – NSW and Narrabri to NorthStar – NSW).

3.2 *Formation design*

The design for the line upgrade comprises excavation to expose cohesive subgrade (generally black soil with *Su* as low as 50 kPa) and backfill with the excavated material using a soil-mixing process. The upper 750 mm of the formation is stabilised with lime and installed in two layers; a treatment termed 'Type E3' as per ARTC ETC-08-03. The design requirement of this material improvement technique is to achieve a UCS greater than 2 MPa and a resilient modulus of 220 MPa at the time of construction. A 50% strength loss for the stabilised soil was allowed within the design, anticipated to account for the loss of lime / leaching / ingress of moisture. A strength loss up to 40% in cohesive materials on soaking was reported by Little (1999).

3.3 *Construction challenges*

The following challenges were identified:

(1) Compacting fill on a firm to stiff clay with *Sr* of 80%.
(2) Developing a methodology for timely strength and stiffness measurement of:
  a) As-constructed earthworks materials.
  b) As constructed lime stabilised materials reaching peak strength several weeks after placement and depending on a range of environmental parameters.
(3) Reconciling strength and stiffness of as-constructed earthworks and stabilised materials with design parameters including resilient modulus and strength.
(4) Reducing environmental impacts by adopting 100% reuse of site won material.

4 ALTERNATIVE COMPLIANCE TESTING TRIAL

4.1 *Trial and high-quality sampling*

Two large scale construction trials were carried out prior to construction to capture a representative range of ground conditions to (i) prove the effectiveness of the earthworks lime stabilisation methodology and (ii) develop an alternative compliance testing procedure using VEDP (PANDA® device) and LWD-PI (ZORN ZFG 3000 device). Trial 1 was located at Gurley and was a 160 m long trial area. Trial 2 was located at Milguy amd was 1km in length. Both sites exhibited high plasticity clay with undrained shear strength (*Su*) ranging from 50 to 60kPa at the underside of the lime stabilised layer.

The construction trials were carried out with the contractor's proposed plant and methodology, such that the trials would:

(1) Replicate full production earthworks methodology
(2) Validate the performance of the stabilised material
(3) Demonstrate that the design parameters would be met.

The Trial 1 area was evenly split to trial two lime stabilised layer arrangements – two 250 mm thickness layers compared to a single, 400 mm thick layer.

Within Trial 2, two 400 mm thickness layers were placed consecutively, resulting in a total thickness of 750 mm of treatment (to allow for 50mm reworking by stabiliser plant).

Extensive field and laboratory testing of each Trial area was

carried out. This comprised compaction testing, nuclear moisture-density gauge, bulk sampling of stabilised material (prior to compaction) for UCS testing (accelerated to three days and seven days), high-quality undisturbed samples (U100) obtained using a custom-made sampler, VEDP, LWD-PI, and Plate Load Tests (PLTs).

Several tests were carried out at regular intervals with time to capture the effect of lime curing. A sub-set of test results is presented in this paper, with further results also presented in an accompanying paper (Blanchet & Yang, 2021).

4.2 *Mixing method*

The mixing of material from the existing rail formation was achieved by:

(1) Excavation to full design depth with a 30 T excavator.
(2) Placement of loose material using a 30 T excavator.
(3) Partial compaction with pad and flat drum rollers.
(4) Mixing using a CAT RM500 stabiliser.

Within (3), the material was trimmed by a grader to establish a consistent layer thickness such that the required lime spread could be effectively applied to achieve a consistent lime content and improve the trafficability of the insitu arrangement for the spreader and water truck

Particle Size Distribution (PSD) testing was completed on the mixed material pre- and post-stabilisation, as illustrated in Figure 4.

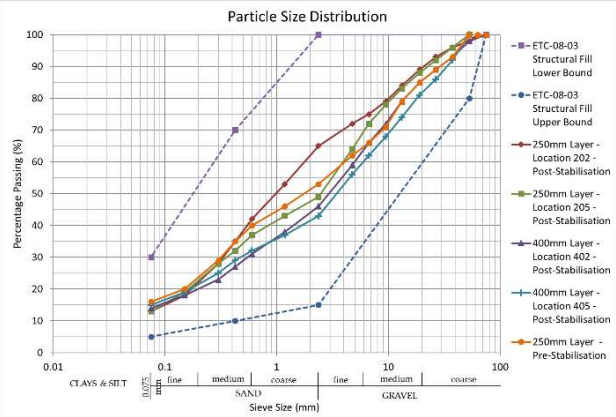

Figure 4. Grading of pre and post stabilisation for Trial 1 – Gurley.

4.3 *Conventional validation using UCS*

UCS tests were completed on Trial 1 samples mixed in the field (2% quick lime), compacted to 95% of SMDD and prepared within 24 hours. For these samples, lime demand test results used for guidance only. In accordance with TfNSW T116, UCS tests were undertaken both at "seven days accelerated" (7DA) (equivalent to 30 day curing) and "Three days accelerated" (3DA). Figure 5 presents the results of both 3DA and 7DA tests.

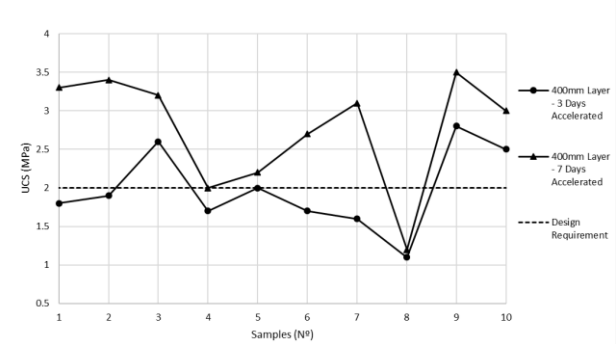

Figure 5. UCS results (three days and seven days accelerated) for samples mixed in the field with 2% quicklime.

As shown on Figure 5, the 3DA tests consistently returned lower UCS values than the 7DA UCS tests, indicating that the 3DA samples may not be fully cured (when compared with the 7DA). Both 3DA and 7DA show strength gain. With the exception of one test, all 7DA UCS tests met the minimum design requirement (i.e. UCS ≥ 2 MPa). The average UCS (7DA) test results was calculated to be 2.76MPa, which gives an average S_u of 1.38MPa for the stabilised material after 30 days of curing.

4.4 *Conventional validation using Plate Load Testing*

Nine PLTs were completed following stabilisation and compaction of Trial 2; Four on Day 3 (post compaction), three on Day 21 and two on Day 43.

The Day 3 PLTs were undertaken at the top of Type E3 layer (350 mm thickness) using a 300 mm diameter plate. The results indicate that the PLT derived reloading cycle modulus (E_{v2}) ranged from 57.8 MPa to 81.6 MPa, with an average of 75MPa.

The results from Day 21 and Day 43 testing demonstrated E_{v2} values ranging from 236 MPa to 400 MPa with an average of 311 MPa, showing an increase over Day 3 illustrating the early strength gain. No clear pattern of difference can be observed between Day 21 and Day 43 results.

Based on the UCS and Trial 2 PLT test results, a site-specific ratio of the average E_{v2} over the average undrained shear strength (Su) was estimated to be 220 (i.e. ≈310 MPa / 1.38 MPa). This ratio is in general agreement with highly over consolidated clays, which have reported E / Su ratio of 200 to 300 for plasticity index (PI) less than 30% (Tomlinson 2001).

4.5 *Conventional validation using compaction testing with nuclear moisture-density gauge*

Nuclear moisture-density gauge tests were carried out within the 400 mm thick layer and for Trial 1 only, and completed at both the surface and from a 100 mm deep test pit (excavated via a smooth bucket). Compaction curves of this material indicated an adjusted Standard Maximum Dry Density (SMDD) of 1.76t/m^3 and Optimum Moisture Content of 14.4%. The adjustment of SMDD was made to take into consideration the effect of oversize particles. The results, as per Figure 6, indicate a lower dry density for testing completed within the 100 mm deep test pit. It is interpreted that the lower results – which fell below the acceptance criteria selected for the project – were associated with (1) the excavation roughness and (2) the possible lower compaction achieved at depth due to the layer thickness (a result also indicated by the VEDP completed at the same location).

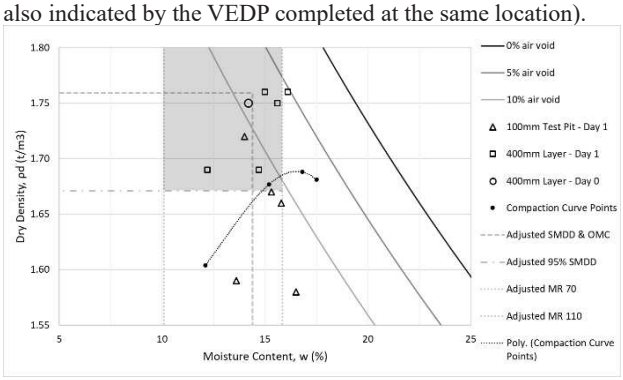

Figure 6. Compaction curve and nuclear moisture-density gauge results.

4.6 *Alternative compliance testing using VEDP*

VEDP tests using a PANDA® device were undertaken at the same locations and time as PLT and compaction testing. The VEDP test results display a full profile of measurements with depth. The VEDP test results were used to derive compaction (dry density) based on an existing publication (Benz-Navarete et al) and published test methodology (NF P 94-105, 2012). The

results indicate that the correlation by Benz Navarete may not apply to capture the strength and stiffness increase with time associated with lime stabilisation of soil comprising a mix of granular and cohesive material specific to this project. Project specific correlations to validate strength and stiffness of lime treated soil have been developed between q_d from VEDP and the results of UCS and PLT.

4.6.1 *Compaction testing using VEDP*

The measured VEDP cone resistance (q_d) and interpreted dry density (t/m^3) using the direct correlation proposed by Benz-Navarete et al is presented as Figure 7. The q_d profiles suggest density varies with depth, compared with a single (composite) value reported by the nuclear moisture-density gauge (direct transmission) device. On Figure 7 the red- and green dashed lines represent density ratios for 95% and 98% respectively; (i) derived via the Benz Navarete proposed correlation (left-hand side of Figure 7); and (ii) directly from SMDD and OMC from the compaction testing (right-hand side). The results indicate that the achieved dry density is generally higher than 95% of SMDD (at Day 0) and thus meets the project's SMDD acceptance criteria.

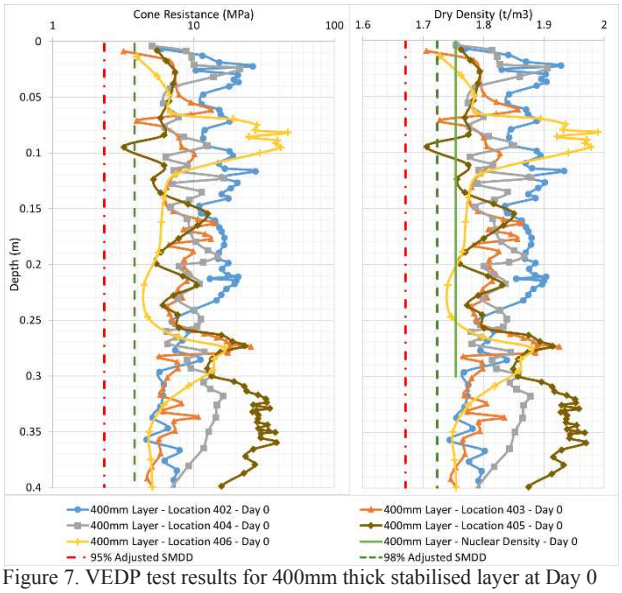

Figure 7. VEDP test results for 400mm thick stabilised layer at Day 0

4.6.2 *Strength and stiffness using VEDP*

The results of VEDP testing – completed at the same time and locations on Trial 2 as the PLTs – were correlated with the PLT results, as presented in Figure 8. The defined relationship was interpreted to demonstrate the minimum design requirements – taken as an E_{V2} parameter of 220 MPa – correlated with a VEDP q_d = 35 MPa (at the time of construction).

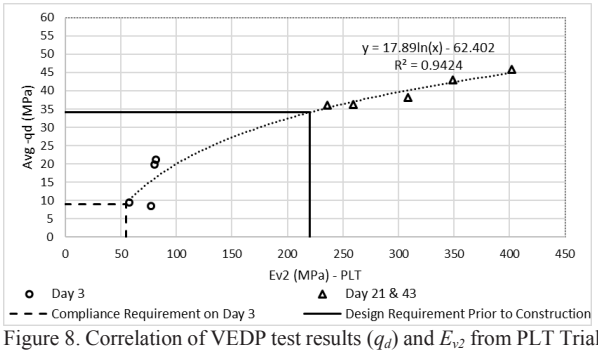

Figure 8. Correlation of VEDP test results (q_d) and E_{v2} from PLT Trial 2.

Adopting the project specific correlations of UCS = 2 x *Su* and E_{V2} / *Su* = 220, the stabilised layer was also deemed to meet the project's minimum design strength requirement (UCS ≥ 2 MPa) once an E_{V2} modulus of 220 MPa was achieved.

As all PLT test results at Day 21 and beyond meet the minimum design resilient modulus and UCS requirements adopting such correlations, the same insitu materials can be assessed for compliance once tested using PLT or VEDP at Day 3 of curing. The minimum requirements for Day 3 assessment were derived to be an PLT demonstrated E_{V2} modulus of 57 MPa or above (and thus UCS ≥ 0.5 MPa based on the project's correlation) or a minimum VEDP measured q_d of 9 MPa. These minimum criteria were referred to for compliance specifications as "early acceptance" thresholds.

VEDP test results (from Trial 1) are presented in Figure 9, and represent an example of the stabilised layer meeting the "early acceptance" compliance requirement, once test results anomalies are accommodated (as per Standard NF P 94-105, 2012).

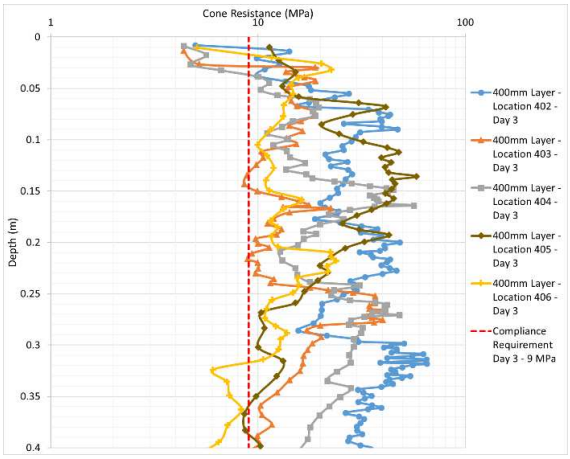

Figure 9. VEDP test results for 400 mm thick stabilised layer at Day 3

4.8 *Alternative compliance testing using LWD-PI*

LWD-PI tests were also completed at the same locations and same time as the PLTs. The LWD-PI results (Modulus $E_{vd\ LWD\text{-}PI}$, in MPa) are compared with the PLT results on the same day (Figure 10). The comparison indicates at Day 3, there is approximate equality between E_{v2} and $E_{vd\ LWD\text{-}PI}$ parameters. However, testing completed on Day 21 and beyond suggest the E_{v2} : $E_{vd\ LWD\text{-}PI}$ relationship is approximately two (with a ± 60 constant for linear relationships).

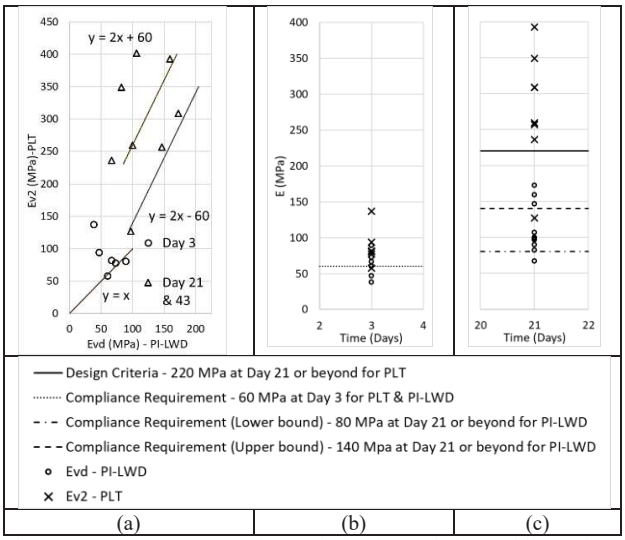

Figure 10. PI-LWD test results (a) derived correlations with E_{V2} from PLT; (b) Day 3 results and calculated minimum compliance requirement; (c) Day 21 results and calculated minimum compliance requirements

These ratios were used to establish LWD-PI test compliance requirements for stiffness – specifically that on Day 3 the minimum acceptance $E_{vd\ LWD\text{-}PI}$ parameter is 57 MPa, whilst for Day 21 and beyond the $E_{vd\ LWD\text{-}PI}$ parameter is required to comply with a value within 80 MPa (lower bound) to 140 MPa (upper bound). Such a wide range may have practical limitation if applied to other projects and further testing is recommended on a project specific basis.

5 APPLICATION OF TRIAL TO CONSTRUCTION PHASE

Based on the trial results, an alternative compliance testing methodology comprising VEDP and LWD-PI was developed in the form of a project-specific specification usable by the Contractor. The objective of the alternative compliance testing regime, as presented herein, was to validate: (1) the design parameters for lime stabilised material (strength and stiffness) including the effect of curing; (2) compaction requirements; (3) demonstrate whether a thicker layer meeting design requirement can be constructed upon a firm to stiff subgrade. The set of developed acceptance criteria, inclusive of 'early acceptance' minimum thresholds that consider the effect of curing and strength increase with time are presented in Table 1.

Table 1. Alternative compliance testing acceptance criteria for stabilized site won materials

Test & Curing Age	Min. Value	Unit
VEDP (q_d) MPa – Day 0	5	MPa
VEDP (q_d) MPa – Day 3 or earlier	9	MPa
LWD Day 3 or earlier	80	MPa

The proposed method comprises direct field measurement allowing for near real time reporting of alternative compliance results at Day 0 and Day 3 from placement and compaction. This project-specific specification complements the traditional compliance testing, whereby traditional testing (nuclear density and associated compaction curve/ Hilf) is still undertaken but at a lower frequency. Accordingly, the by-product of adopting the alternative compliance testing regime are the significant time savings achievable, resulting in a reduced laboratory workload and time lag to achieve insitu test finalisation.

To account for the variability of measurement inherent to the VEDP and LWD-PI assessment methodology, a test 'location' defined within project specific specification represents a series of 3 VEDP tests and 3 LWD-PI along with a comparable compaction test (using a nuclear moisture-density (direct transmission gauge) at the surface of the 400 mm layer. In order to rapidly evaluate a non-compliance measurement, a re-test methodology for VEDP and LWD-PI has also been established. This spatial layout of this re-test methodology is illustrated in Figure 11.

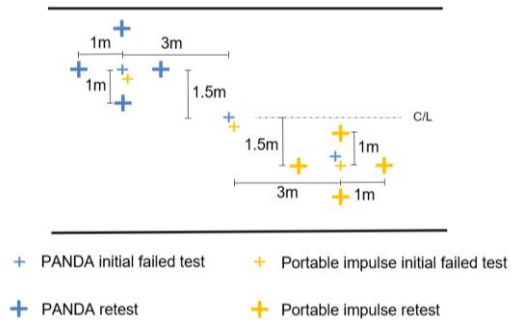

Figure 11. Graph showing compliance retest methodology developed for the project specific specifications.

6 CONCLUSION AND DISCUSSION

The full-scale construction trial and alternative compliance testing presented herein has been utilised to derive a project-specific Specification that can effectively:

(1) Verify as-constructed formation materials meet the design nominated strength and stiffness requirement via use of a combination of the VEDP and LWD-PI insitu test techniques.

(2) Evaluate and validate compaction (and uniformity thereof) through thicker fill layers. If validated via traditional testing methodology, this would require time consuming excavations through the compacted fill materials (and have a resulting risk of post-testing defects due to intrusive testing and requirement for test site repair).

Use of the proposed alternative insitu test methods is encouraged as a complement to traditional compliance testing. The ease and rapidity of LWD-PI and VEDP testing allow the development of practical re-test procedures and a visualisation of material performance with depth (i.e. full thickness profiling).

The study presented in this paper demonstrates the importance and value of carrying out a full-scale trial combined with high quality testing and a strong collaboration with the Contractor. The results of this arrangement has allowed 100% material re-use throughout the project, such that a stabilised structural formation has been constructed without the need for importation of structural fill; thereby significantly reducing the project's environmental impact.

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