DESIGN OF RAIL FORMATION AND SUBGRADE – MATCHING TESTING TO DESIGN PARAMETERS

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SUMMARY

Field assessment methods such as the use of Light Weight Deflectometer (LWD) for compliance testing of earthworks and pavement construction have developed significantly over the last 15-20 years. Adopting such methods for rail formation compliance testing would be beneficial to the Australian rail industry.

Mechanistic rail formation design typically uses stiffness and strength parameters, while construction compliance relies heavily on California Bearing Ratio (CBR), density and moisture testing. Using these tests adds a significant time lag during construction.

This study presents the resilient modulus from LWD for capping, structural fill, general fill and at foundation level, together with an example of near real-time reporting of the results using a geospatial platform. The LWD resilient modulus results are compared to cyclic triaxial test results at foundation level as well as Dynamic Cone Penetration (DCP) and Shear Vane Tests (SVT). The results indicate that the LWD may be used in combination with reduced traditional compliance testing frequency to save on time and laboratory testing effort.

1 INTRODUCTION

This paper presents the results of LWD field testing carried out on a rail project, with correlation to the standard earthworks compliance results in the same areas. Laboratory testing was also carried out, however, the results were not available at the time of submitting this paper. Test methods including LWD testing are currently used in the road and rail industries in Europe and the USA.

The field testing was carried out on Inland Rail's (IR) Parkes to Narromine (P2N) project in north-west New South Wales which comprises an upgrade of the existing rail track as part of the 1700km-long Melbourne to Brisbane Inland Rail Program, delivered by the Australian Rail Track Corporation (ARTC). The P2N project includes reconstruction of the rail formation and track between Parkes and Narromine, a distance of approximately 100km. The alignment crosses gently undulating terrain and several broad flood plains.

This paper follows on from recent papers relating to the Li D and Selig T [1] rail formation design method [2] and to stress distribution in layered rail formation [3]. It presents the results for the rail formation compliance testing on the IR project along with discussion of the results in the context of the IR formation design.

The IR formation design methodology presented in the previous papers is based on a mechanistic approach and considers stress distribution within the formation, cumulative plastic deformation and unsaturated soil behaviour. Compliance testing aligning with this design includes undrained shear strength, moisture content and in situ density. This testing regime for both subgrade and formation materials would benefit from alternative test methods such as LWD.

The LWD is widely used for roads construction compliance testing to verify resilient modulus of earthworks fill. Resilient modulus is also an input analysis parameter for mechanistic formation design. Measuring resilient modulus as part of earthworks compliance testing will assist in validating the design assumptions and parameters to complement compaction testing.

2 DESCRIPTION OF MATERIALS TESTED

The soil types and earthworks within the P2N project generally comprise capping, structural fill, general fill and ground at foundation level. Figure 1 illustrates the material layering for the rail formation.

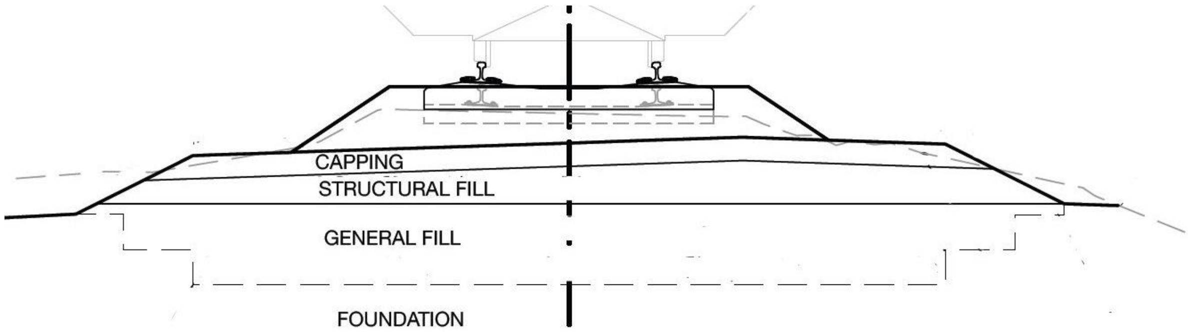


Figure 1: Summary of material designation in accordance with ARTC ETC-08-03

These four types of material shown on Figure 1 were tested during the LWD testing campaign and are described in the following sections. The material properties are defined in the Australian Rail Track Corporation (ARTC) earthworks specifications ETC-08-03.

2.1 Foundation Level

On the P2N project the foundation level generally comprised medium to high plasticity clay. Where the foundation lay within the existing rail formation extent the clay was generally wetter than the plastic limit.

The foundation level preparation, based on the strength requirements in the design, consisted of one of the following treatments:

- Leave in place
- Loosen, moisture condition and compact
- Excavate and replace
- Lime stabilisation

2.2 General Fill

The general fill was observed as a sandy clay with gravel, generated from the re-use of existing formation material (ash and fouled ballast) combined with clay from the foundation level. The mix was stabilised with 1.5-2.0% of quick lime.

2.3 Structural Fill

The structural fill was an imported material, observed as sandy gravel with clay when placed. The characteristics of the structural fill varied depending on its source.

2.4 Capping

The capping was a manufactured and imported material, observed as clayey gravel with sand when placed.

3 TESTING REGIME

3.1 Standard Compliance Testing

The design and associated specifications require a series of compliance tests during construction. The testing was carried out in accordance with the project specification and ARTC specifications ETC-08-03 and ETC-08-04. The standard compliance testing requirements for fill materials include Atterberg limits, Particle Size Distribution (PSD), CBR and compaction testing.

For foundation level (generally in natural cohesive material), Dynamic Cone Penetrometer (DCP) testing was carried out to 2m depth or prior refusal. Where DCP results were low, Shear Vane testing (SVT) was carried out at 0.1m intervals to 0.3m deep or refusal.

Some of these tests (such as CBR, and compaction curve for MDD) are time consuming, resulting in significant lag time (up to several weeks) between the placement of the fill layer and issue of certified test results.

3.2 Light Weight Deflectometer (LWD) Testing

LWD testing was carried out at several locations along the P2N alignment for soil encountered at foundation level, general fill, structural fill and capping. The LWD testing carried out is summarised in Table1 with the corresponding compaction compliance testing frequency requirements.

Material type	No. of LWD tests	LWD test frequency	Standard Compaction Testing frequency
Capping	104	5 tests at 20 m centres (40 test per $1000m^2$)	Density testing at 1 per 1000 m^2/layer
Structural Fill	124 [1, 2]	3 tests at 20 m centres (24 test per $1000m^2$)	Density testing at 1 per 1000 m^2/layer
General fill	113	5 tests at 20 m centres (55 test per $1500m^2$)	Density testing at 1 per 1500 m^2/layer
Foundation level	238 [3]	1 to 5 tests at 8m centres	DCP and SVT at 8m centres

Table 1: Locations of LWD testing

[1] *LWD testing was also carried out at the same locations as standard compliance testing*
[2] *LWD testing was also carried out on culvert structural backfill during and after compaction*
[3] *LWD testing was carried out adjacent to and at the same time as the standard compliance tests*

4 LWD TEST

4.1 Device Description

The LWD measures a dynamic resilient modulus that is specific to the LWD device used. In this study the dynamic resilient modulus was measured using the LWD and referred to as Ev_{LWD}. The measured Ev_{LWD} can be correlated to dynamic resilient modulus. The dynamic resilient modulus is an analysis input parameter for the stress distribution of train load within the formation.

A Zorn ZFG 3000 LWD was used for this study. The device used has an integrated GPS. The measured Ev_{LWD} is displayed on the device immediately on completion of the test and is stored electronically together with the relevant GPS coordinates. This allows for the results to be reported in near real-time to a geospatial platform. Further details of reporting are presented in Section 8.

4.2 LWD Testing Description

LWD testing generally comprises dropping a weight onto a plate in contact with the surface to be tested with accompanying measurement of deflection of the soil under the weight. The size of the plate can be varied depending on the layer thickness intended to be tested. Following an application of three seating blows, measurements of the weight are taken to provide a dynamic resilient modulus. Illustration of the test is shown in Figure 2.

The LWD test method used in this paper is based heavily on ASTM E2835-11 *Standard Test Method for Measuring Deflections using a Portable Impulse Plate Load Test Device.* It is noted that there is not yet a standardised test method for Australian use.

Figure 2: LWD testing of lime treated general fill using the Zorn device 13/12/19

5 LWD MEASUREMENT

The LWD device measures dynamic resilient modulus Ev_{LWD} (MPa), relative penetration speed s/v (mm/s), and deflection amplitude (mm).

6 LWD TEST RESULTS INTERPRETATION

6.1 Foundation Level

The results from the SVT and DCP were used to derive undrained shear Strength (Su). Undrained shear strength from SVT was obtained from the Shear Vane calibration factor. Undrained shear strength from DCP was obtained using a correlation developed as part of the detailed design.

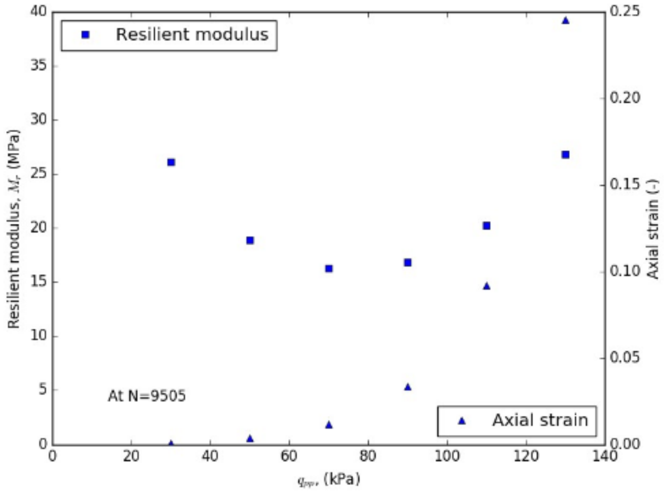
The undrained shear strength values varied between 25kPa and 240kPa at foundation level. The test results also indicate that Su obtained from SVT was generally higher than that obtained from DCP.

6.1.1 Relationship between Ev_{LWD} and undrained shear strength

Ev_{LWD} were compared with the results from the Cyclic Loading Triaxial testing carried out on an undisturbed clay sample collected at fill foundation level on a project with similar brownfield conditions. The results of the Cyclic Load Triaxial testing were presented in a previous paper [2]. Further details are presented below.

Staged cyclic load testing with 10,000 cycles for each stage was carried out. For each stage (five in total, Stages 1 to 5) a different cyclic deviatoric stress was applied: 30kPa, 50kPa, 70kPa, 90kPa and 110kPa. The frequency was set at 2Hz.

Laboratory results for the sample tested are presented in Figure 3***.***



Measurement	Value
Gravimetric water content (w)	
Initial:	24%
Final:	30%
Specific gravity (Gs)	2.63
Initial void ratio (e0)	0.67
Initial degree of saturation (Sr)	94.2%
Initial dry density (γdry)	1.57t/m3
Su (top)	82.0kPa
Su (bottom)	62kPa

Figure 3: Cyclic triaxial laboratory results, graph shows end of stage resilient modulus versus target deviatoric stress amplitude

Deviatoric stress level expected in the foundation based on numerical modelling [3] ranges from 40kPa to 80kPa depending on the formation design and associated geotechnical treatment. Figure 3 indicates that, for this deviatoric stress range, the dynamic resilient modulus at the end of stage ranges from 15-20MPa.

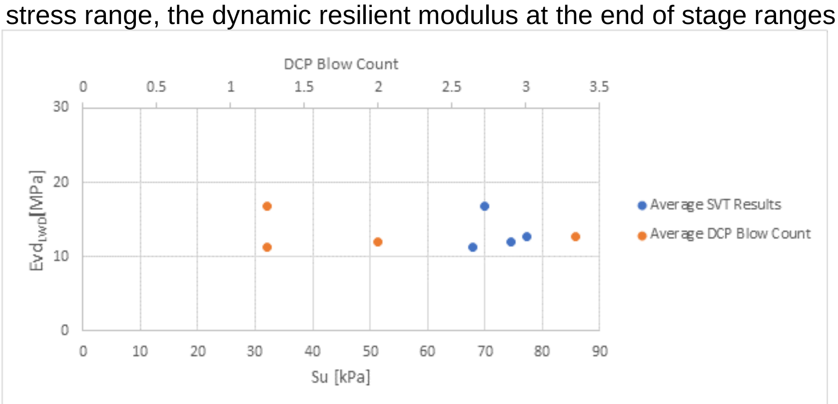


Figure 4: Ev_{LWD} where SVT compliance testing Su ranged between 40 and 80kPa

Ev_{LWD} where undrained shear strength ranged from 40kPa to 80kPa was extracted and is presented in Figure 4. The results indicate that where undrained shear strength ranged from 40 to 80kPa, Ev_{LWD} ranged from 11 to 17MPa. This is consistent with the finding of the Cyclic Load Triaxial test at similar deviatoric stress (Figure 3). On this basis, the ratio of Evd to EV_{LWD} is approximately 1 for this stress range and material.

A relationship between resilient modulus Evd and undrained strength for deviatoric stress between 40kPa and 80kPa was adopted and is presented below (1) to allow a comparison with SVT and DCP test results.

i. $$Evd_{Su\ \&\ DCP} = Ev_{LWD} = 214 \times Su \qquad (1)$$

Where $Evd_{Su\ \&\ DCP}$ (MPa) is dynamic resilient modulus based on SVT and DCP, Ev_{LWD} (MPa) is LWD dynamic resilient modulus and Su (kPa) is Undrained Shear Strength.

For this study the relationship was assumed linear with deviatoric stress increase, to allow a comparison with SVT and DCP tests results. The cyclic test results indicate that the relationship may not be linear, but influenced by material type and applied deviatoric stress. Further work should be carried out such as cyclic triaxial testing for a range of deviatoric stress conditions for the material used.

The Ev_{LWD} and $Evd_{Su\ \&\ DCP}$ from testing at foundation level are presented in Figure 5. It can be seen that the resilient moduli based on LWD are generally lower than those derived from SVT.

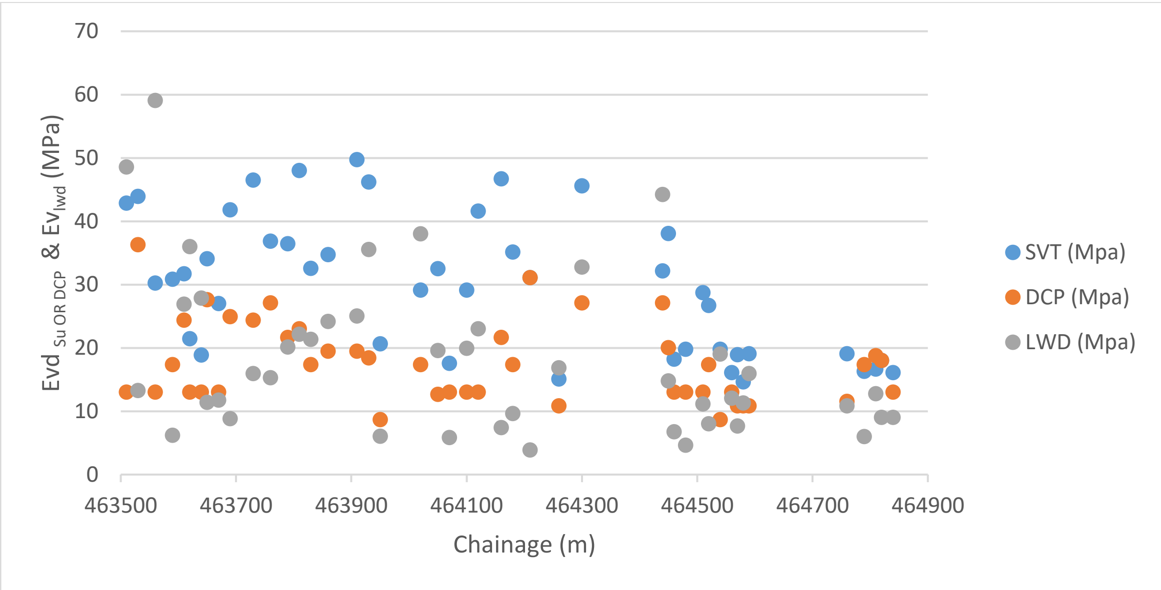


Figure 5: Ev_{LWD} and $Evd_{Su\ \&\ DCP}$ on foundation level from chainage CH463500 and CH464900

6.1.2 Ev_{LWD} at fill foundation level

The Ev_{LWD} results from tests carried out at foundation level prior to remediation of soft spots are plotted on Figure 6. together with published lower bound values [1] for firm cohesive soil (10MPa, red solid line). Figure 6 indicates that 90% of the measurements are higher than 10MPa. This is generally consistent with Undrained shear strength from SVT with 100% of the results higher than 25kPa.

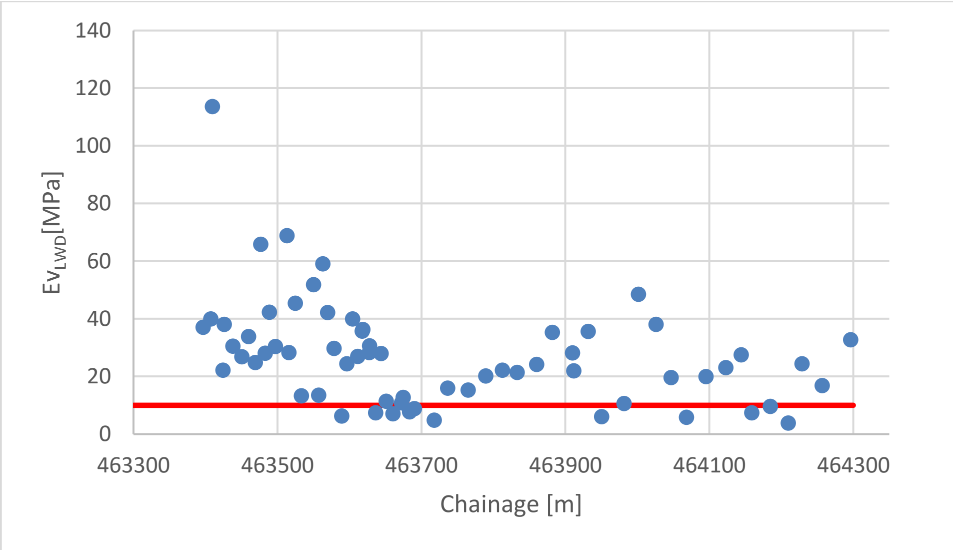


Figure 6: Ev_{LWD} plotted with published (10MPa, red solid line) on foundation level for CH463300 to 464300

6.2 General Fill

The LWD dynamic resilient modulus Ev_{LWD} results carried out on general fill treated with lime was plotted in Figure 7 together with published lower bound values [4] for very stiff soils (43MPa, red solid line). Figure 7 indicates that 100% of the results measured are greater than 43MPa.

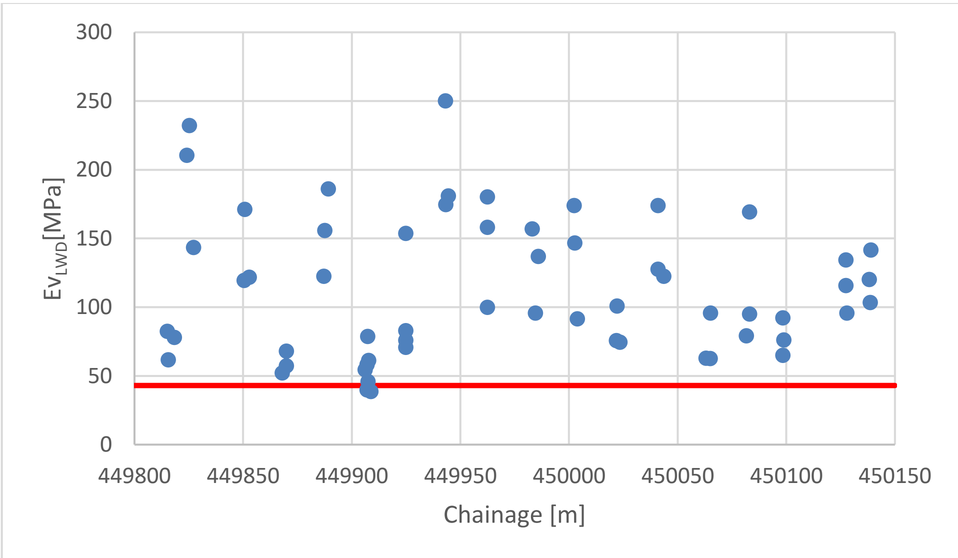


Figure 7: Ev_{LWD} plotted with published data (red solid line) for general fill stabilised with quick lime, two weeks after stabilisation from CH460150 to CH460400

6.3 Structural Fill

Structural fill was tested at two locations: Location 1 within formation adjacent to compliance testing and Location 2 during and after its placement within formation.

Structural Fill LWD testing Location 1: Five LWD tests were carried out at the same location where compliance testing had been carried out. The results of the LWD testing and field results of nuclear densometer testing are presented in Table 2. The results from the LWD were readily available, whilst the certified test results for compaction are pending availability at the time of writing.

LWD testing	**Compliance testing**	
Ev_{LWD} (MPa)	**Compaction testing**	**Material properties**
Available on 11 December 2019 5 tests carried out: 98.04, 66.77, 45.82, 100.22, 62.50 Average is 74.67MPa	Available early 2020 (pending) Wet density OMC Moisture	Available early 2020 (pending) CBR PI WPI

Table 2: Structural fill Location 1 - LWD testing and compliance test results summary

Structural Fill LWD testing Location 2: The LWD dynamic resilient modulus Ev_{LWD} results carried out on structural fill at 20m intervals are plotted in Figure 8 together with published lower bound values [4] for dense cohesionless soils (red solid line, 34MPa).

The Ev_{LWD} ranged from 40MPa to 235MPa (Figure 8) with a standard deviation of 42. ***Figure 8*** indicates that 100% of the moduli of resilience from LWD testing measured are greater than 34MPa. A significant difference in material was observed at the surface of the structural fill from chainage 459390. This appeared to be reflected in the LWD results with a general increase in modulus with increasing chainage.

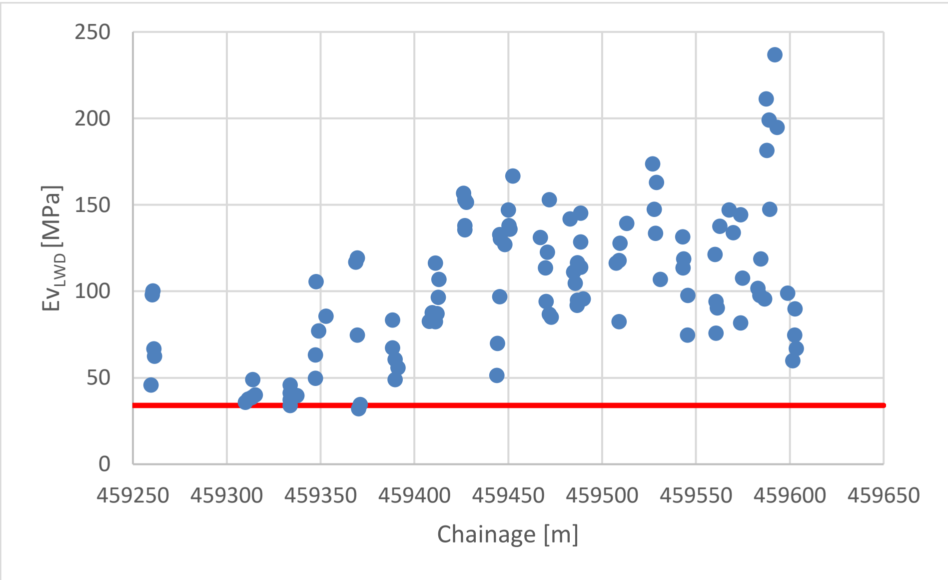


Figure 8: Ev_{LWD} plotted with published data (red solid line) for structural fill from CH459250 to CH459650

6.4 Capping

Capping was tested along a 700m stretch of formation across two lots. Lot 1 extended to CH463390, with Lot 2 extending beyond this chainage. Lot 1 compaction values were less than the compliance acceptance criteria and the Lot was still in the process of being compacted, whilst Lot 2 had met compliance acceptance.

For Lot 1, Ev_{LWD} ranged from 36Pa to 71MPa with an average of 54. For Lot 2, Ev_{LWD} ranged from 73Pa to 241MPa with an average of 140. The Ev_{LWD} results for capping are plotted in Figure 9, together with published lower bound values [1] for capping (80MPa, red solid line). Figure 9 indicates that 0% of LWD results within Lot 1 exceeded 80MPa, compared to 99% for Lot 2. As expected, the measured Ev_{LWD} were significantly higher in Lot 2 which had met compliance acceptance criteria. These results are plotted in conjunction with a traffic light criteria system in Figure 10.

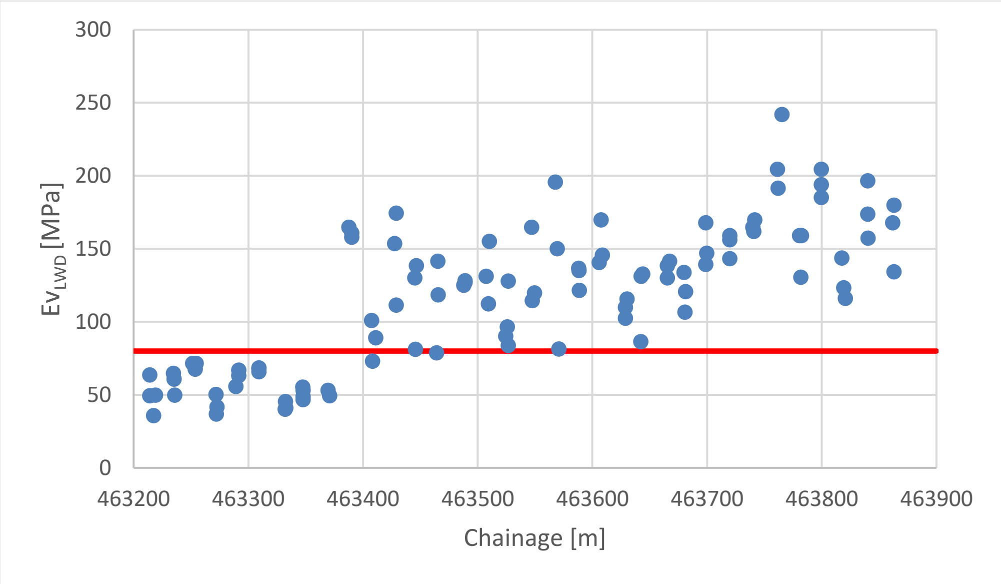


Figure 9: Ev_{LWD} plotted with published data (red solid line) for capping from CH463200 and CH463900 (Lot 1 and Lot 2)

7 LWD TESTING DISCUSSION

7.1 LWD On Foundation Level

The LWD dynamic resilient modulus Ev_{LWD} provided similar results to the those of Cyclic Loading Triaxial test for the deviatoric stress applied, ranging from 40kPa to 80kPa. This stress level is typically expected at fill foundation level (from 1m below formation level – or top of capping) based on analysis carried out on a similar project [3].

The Ev_{LWD} for cohesive soil at foundation level prior to geotechnical treatment were consistent with previously published data for stiff cohesive soils [1], and for stiff to very stiff clays using the scheme from Barounis N [4]. It should also be noted that the LWD testing was carried out prior to geotechnical treatment / removal of soft spots.

7.2 LWD On Fill

The Ev_{LWD} measured are generally consistent with previously resilient modulus data. To develop site specific resilient modulus correlation to Ev_{LWD} where implementation of LWD is sought, both trials and laboratory testing are recommended. This can be easily implemented at the start of construction and will save on testing time and reporting effort as further detailed in Section 8.

The resilient modulus measured on site using LWD on structural fill and capping indicate an increase with compaction similar with compaction testing (Nuclear Density with the measurement of dry density).

The scatter of LWD results should be compared with those obtained from compaction testing (pending at the time of the preparation of this paper).

8 REPORTING OF RESULTS

The results of the LWD were uploaded into a geospatial platform, which allowed for representation of the results in direct comparison with their compliance lot. A traffic light presentation (green, amber, red) was developed using:

- published information [1] as the lower of two criteria (between red and amber)
- an estimate from a mechanistic analysis of track formation design [3] to give the higher criteria (between amber and green).

The resulting output from this study is displayed on Figure 10.

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The relative scatter of results indicates a need for statistical analysis in the use of the LWD as a compliance test. Singh et al [5] noted a scatter of results based on testing carried out at Highland Valley Copper Mine.

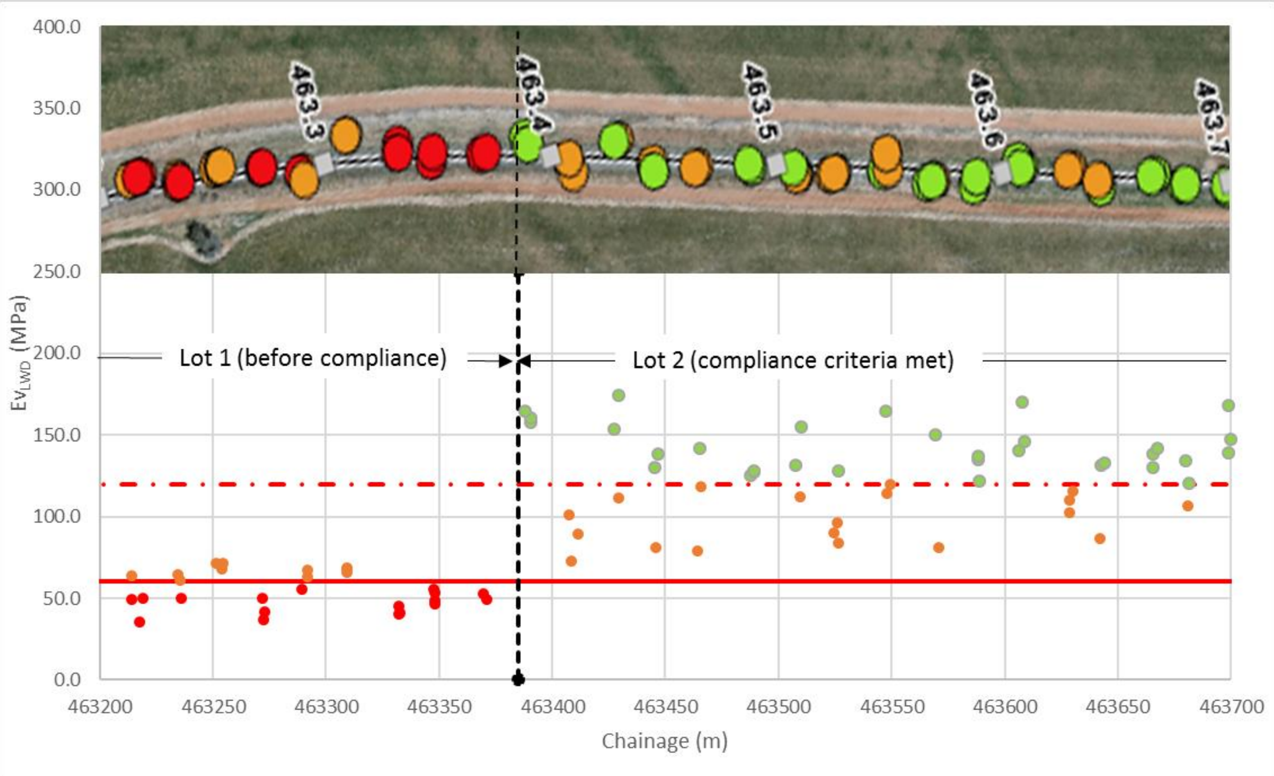

Figure 10: Geospatial reporting of LWD results

9 CONCLUSIONS

The trial carried out indicates that use of LWD testing can provide significant time savings and a reduction in laboratory testing effort. It provides results that correlate directly to parameters used in mechanistic design of the track formation.

Table 3 presents a summary of advantages and disadvantages of LWD and traditional compliance testing (based on CBR and compaction testing) to measure the earthworks material characteristics against the design input parameters.

Testing	Advantage	Disadvantage
CBR and compaction testing using nuclear densometer	Provides a limited indication of wet strength (4 day soaked)	Low repeatability of CBR test [6] High variation in the conversion between these index tests and design input parameters (strength and stiffness) Time lag of up to several weeks was noted to the final density results partially due to the time required to create a compaction curve in the laboratory
LWD	Results available in near real time Direct correlation to design input parameters for performance-based design Can be used to reduce compaction compliance testing frequency (with an increased frequency of LWD)	Scatter of results requires trial testing to establish relationship between LWD, strength and stiffness parameters Requires correlation for each material used

Table 3: Summary of advantages and disadvantages of LWD and traditional compliance testing

Whilst the results provided an initial correlation between EV_{LWD} and undrained strength for a specific material (cohesive foundation) and a limited stress range, further work is required to determine appropriate correlations for other materials and stress ranges. For this study the relationship was assumed linear with stress increase, to allow a comparison with SVT and DCP tests results. The literature review indicates that this relationship is non-linear.

As noted in previous research, there is a relative ‘scatter’ of LWD results across tested materials. In the case of this paper, testing of a manufactured fill material with relatively uniform compaction also displays scatter, with a coefficient of determination (R^2) of 0.225 for the compliant Lot 2 displayed in Figure 9. Whilst it is recognised that this is a high variance, it should also be noted that the LWD testing regime carried out has a significant number of tests carried out within a lot – far more than the standard compliance testing requirement. A study of the variance for standard compliance tests carried out at the same frequency as LWD would be beneficial.

10 REFERENCES

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