NACOE
NATIONAL ASSET CENTRE OF EXCELLENCE

FINAL REPORT

P60: Best Practice in Compaction Quality Assurance for Pavement and Subgrade Materials (2020–21 Year 5)

ARRB Project No.: 015731

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Summary

The current industry practice relies on the use of in situ dry density ratio (DDR) to control the quality of compaction during the construction of earthworks. The main reason is because the density measurements are relatively easy to undertake during construction, and the parameter itself is precise and with limited variability. However, this approach has two major disadvantages, namely: (i) the in situ modulus of the layers is not directly measured, and (ii) there is a significant delay between the time of undertaking the DDR measurement and the delivery of the final test results. Such a (routine) delay in the provision of test results can lead to costly rework being required by the contractor if earthworks are found to be non conforming and require remediation after the works have further progressed. To address the above issues, this National Asset Centre of Excellence (NACOE) research project investigated the viability of using alternative testing techniques to control the quality of constructing earthworks.

This five-year study investigated a range of alternative testing devices, such as the light weight deflectometer (LWD), Clegg Hammer and PANDA probe with a focus to evaluate their effectiveness in assessing the quality of the earthworks constructed. A methodology has been developed to adopt the LWD as an alternative QA method. However, the methodology is equally applicable for other similar technologies.

The report presents the final research outcomes to allow the adoption or trialling of this alternative approach in future roadwork construction projects. The final deliverables include the proposed amendments to MRTS04 *General Earthworks*, and a technical note that details the technical basis and approach. Throughout the project, a number of webinars have also been presented to disseminate the findings and as an avenue to seek industry feedback.

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1. Introduction

1.1 Background

The current industry practice relies on the use of in situ dry density ratio (DDR) to control the quality of compaction during the construction of earthworks. The main reason is because the density measurements are relatively easy to undertake during construction, and the parameter itself is precise and with limited variability. However, this approach has two major disadvantages, namely: (i) the in situ modulus of the layers is not directly measured, and (ii) there is a significant delay between the time of undertaking the DDR measurement and the delivery of the final test results. Such a (routine) delay in the provision of test results can lead to costly rework being required by the contractor if earthworks are found to be non-conforming and require remediation after the works have further progressed. To address the above issues, this National Asset Centre of Excellence (NACOE) research project investigated the viability of using alternative testing techniques to control the quality of constructing earthworks.

This five-year study investigated a range of alternative testing devices, such as the light weight deflectometer, Clegg Hammer and PANDA probe with a focus to evaluate the earthwork quality achieved during construction. These testing devices not only provide timely feedback to the construction team, but also have a better accuracy when compared against reference standard testing such as the plate load test (PLT).

Year 1 of the project completed a comprehensive literature review on the available alternative testing devices, while Years 2 and 3 conducted field trials to compare density and in situ stiffness measurements using these alternative devices. The field trials validated the lack of direct correlation between density and in situ modulus measurements. Furthermore, it was observed that the in situ modulus measurements reflect the actual field conditions taking into account the change in modulus as a result of changes in moisture content and compaction efforts.

In Year 4, the project focused on disseminating the results from the previous years to industry through a series of online webinars.

In Year 5 (this report), the focus was to implement the technology on construction projects across Australia. This provided the opportunity for industry to provide feedback and subsequent modifications to draft TMR technical note – *Guidance on Use of Light Weight Falling Deflectometers (LWDs) to be Accepted as an Alternative Method for Verification of Earthworks Compaction Requirements,* and amendments to MRTS04 *General Earthworks* (Queensland Department of Transport and Main Roads 2020).

1.2 Project Objectives

The objectives of this project were:

1. To identify and validate potential field methods to measure in situ stiffnesses.
2. To update the process for quality assessment of earthworks.
3. To disseminate the research findings to industry to facilitate adoption of the new technology.

The methodology adopted was as follows:

- Task 1 – Collect feedback, address outstanding issues and prepare an implementation plan for TMR. This included engaging selected consultants in the industry and receiving feedback from civil contractors.
- Task 2 – Draft recommended changes to MRTS04. There is a possibility that MRTS04 (TMR 2020) is not the most appropriate format for incorporating the suggested changes. This may lead to including a clause in it with a reference to a separate technical note.
- Task 3 – Prepare a final-year report.

1.3 Report Structure

This is the final report for the project and is structured as follows:

- Background and project objectives are covered in Section 1.
- Section 2 provides a summary of the outcomes from the previous years of the project.
- Section 3 presents the proposed changes to MRTS04 to allow the implementation of the alternative testing methods.
- Section 4 presents a revised technical note based on industry implementation and feedback received.
- Section 5 outlines the conclusions and recommendations.

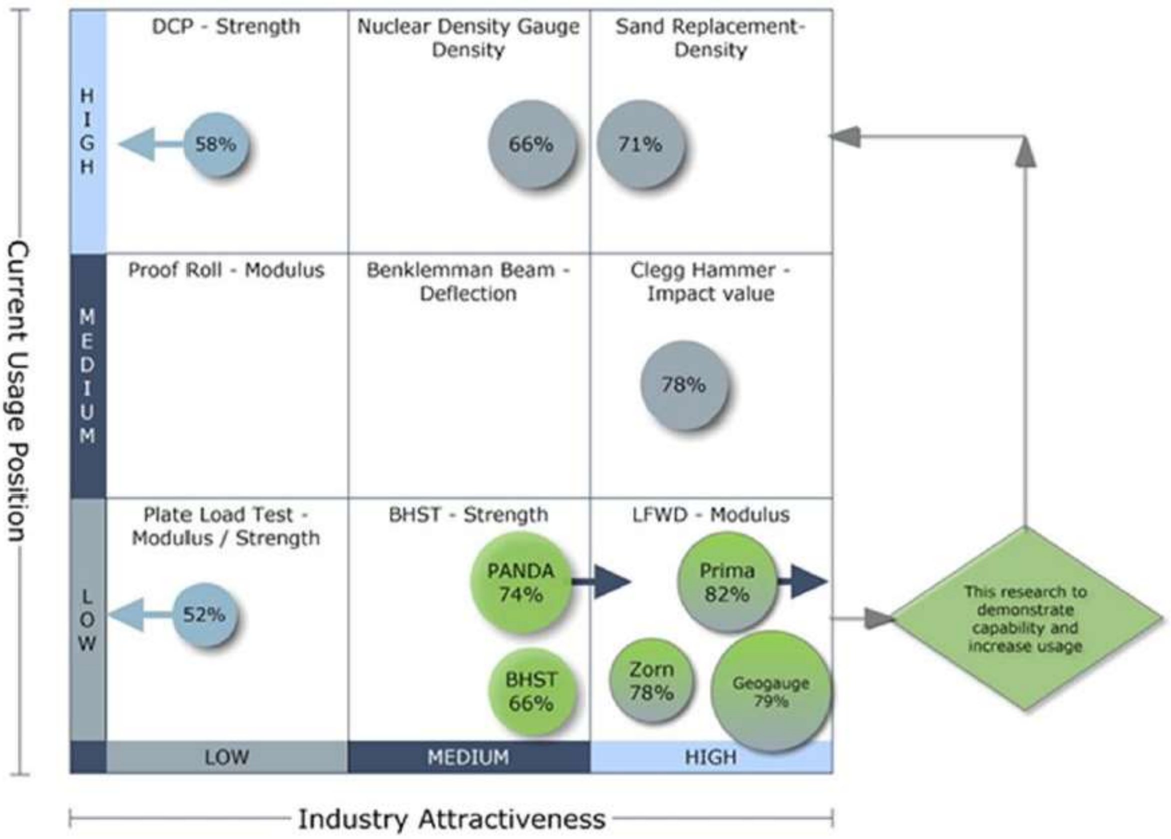
2. Summary of Work Completed in Previous Years

2.1 Year 1 (2016–17)

A literature review (Lee et. al 2017) was conducted in 2016–17 (Phase 1) which selected several testing devices to be evaluated that have the potential to minimise turnaround time for test results and possibly offer a direct modulus measurement. Figure 2.1 shows the relationship between industry attractiveness and current usage of the devices evaluated, where industry attractiveness is a metric comprised of cost, test duration, accuracy, etc.

The main output of Phase 1 was a shortlist of devices that showed a high attractiveness – indicated by the percentage inside the labels shown in Figure 2.1. The PANDA, Zorn, Geogauge and Prima devices proved to be the most promising.

Figure 2.1: Industry attractiveness – current usage strength matrix (Phase 1)



Source: Lee et al. (2019)

2.2 Year 2 (2017–18)

Testing using the above equipment was carried out in 2017–18 (Phase 2) (Lee et al. 2019) to assess their suitability for use as testing devices in construction. The following equipment (as shown in Figure 2.2) was used at roadwork construction projects in Ballina, NSW, and Rocklea, Qld:

- light falling weight deflectometer (LWD) – Prima 100 manufactured by Sweco
- light falling weight deflectometer (LWD) – Terratest 5000 manufactured by Terratest

- Clegg Hammer – manufactured by GSR Laser Tools
- H4140 soil stiffness gauge (SSG) or also known as Geogauge – manufactured by Humbolt
- PANDA probe (variable energy dynamic penetrometer)
- dynamic cone penetrometer (DCP).

Figure 2.2: Equipment evaluated in Year 2 of the project

Source: Lee et al. (2019).

A key finding from Year 2 was that a higher density did not necessarily correspond with a higher modulus value. The study also highlighted that the outputs of some of the alternative tests were dependent on material properties, which meant that the actual test value needed to be calibrated to be meaningful in terms of how it related to the design or specification values.

It was concluded from Year 2 that there were clear benefits associated with adopting tests other than density testing to evaluate the material strength and modulus properties achieved during construction. It was therefore agreed that new procedures and standards need to be developed to promote the use of these alternative devices in Phase 3 of the project (Lee et al. 2019).

2.3 Year 3 (2018–19)

Additional field testing was conducted on the Smithfield Bypass Project near Cairns where construction started in late 2018 (Lee et al. 2020a). Extensive field testing was carried out to compare the test results collected using conventional techniques with test results collected using the alternative testing devices identified in Year 1.

Additionally, the field testing included the evaluation of the ability of the alternative devices to be used on construction sites and produce interpretable results within a relatively short time period (e.g. within 24 hours). A method specification for the use of these alternative devices was also developed based on the findings from the field testing undertaken.

2.4 Year 4 (2019–20)

In Year 4 , a technical note was developed that provides a detailed roadmap for the derivation of a project-specific or material-specific specification that would facilitate the implementation of the use of LWD devices as valid earthworks QA testing tools (Lee et al. 2020b).

This was followed by the presentation of two online webinars which focussed on the dissemination of the research findings and recommendations from Years 2–4. An additional webinar was delivered that included a leading international researcher from the USA and presented a practical example of the Australian application of an LWD on an actual railway construction project to share the findings and experience with the modulus-based testing methods.

A draft technical note was also developed that formalised the recommendations relating to field implementation of the LWD. A similar approach can also be applied to other alternative testing equipment that measures in situ modulus.

3. Proposed Changes to MRTS04

In order for the TMR to adopt the alternative quality assessment technique developed in previous years, it is essential that MRTS04 (TMR 2020) is amended to allow such methods to be used or trialled on construction projects. This also forms part of the TMR implementation strategy to disseminate the research findings from NACOE.

A large part of the proposed changes to MRTS04 was based on the feedback received from recently completed project-specific use of the LWD in Australia. The following two projects have adopted the new approach:

- earthworks components of the Snowy 2.0 project (which was being undertaken under a project-specific version of R44 – *Earthworks*) (Transport for New South Wales 2020
- the Wide Bay Highway Upgrade Project (which was undertaken in accordance with MRTS04 (Queensland Department of Transport and Main Roads 2020)).

Section 3.1 presents the proposed amendment to Clause 15.2.1 for adoption in MRTS04. References are made in the proposed inclusion to existing clauses in the specification, and the key items in the proposed revision include:

- the requirement for suitable site-specific testing of an alternative method of compaction assessment to be undertaken on-site, initially alongside accepted test methods (i.e. on a trial area where side-by-side testing is undertaken)
- suitable evaluation of the resulting paired data, including the identification of the range of material conditions assessed during the trial and the influence of moisture content (if any) on any proposed acceptance thresholds that would be adopted for the proposed alternative method of compaction assessment.

3.1 Proposed Wording for Insertion in Clause 15.2 of MRTS04 – General Earthworks

Clause 15.2.1 Use of Alternative Methods for Compaction Assessment

Alternative methods for verifying earthworks compliance with compaction requirements may be adopted if the Contractor can demonstrate to the Administrator that the proposed testing technology and methodology can achieve similar compliance outcomes. Such alternative test methods could include the use of light weight deflectometer (LWD) technologies that comply with Test Method Q258A or Q258B as detailed in TMR's *Material Testing Manual* (MTM).

Prior to adoption it would be expected that project-specific verification testing will be undertaken, such that the alternative test method proposed has suitable acceptance criteria defined that reflect the minimum density requirements as identified in Table 15.3(b). The use of generic or equipment manufacturer's supplied acceptance criteria is not considered sufficient, and a quality control validation is required.

Project-specific verification testing should be sufficient to define and evaluate:

- the equipment brand and manufacturer that is proposed to be utilised for compliance testing
- the standard test configuration that is proposed to be utilised for compliance testing
- material units/sources that have been validated for use and will be subject to alternative method of compaction assessment
- the moisture condition and in situ density range of compacted materials that have been validated for use with the alternative method of compaction assessment
- the effect (if any) of in situ moisture condition on the defined acceptance threshold
- comparison of the effectiveness of alternative methods of compaction assessment with compliance testing if undertaken in accordance with Clause 15.2

- technical details for the proposed project-specific specification, including clear identification of the method of assessment, acceptance criteria and the method for ongoing verification of alternative testing regimes.

Note that the Administrator's acceptance of an alternative method for verifying compliance does not, unless specifically stated, alter the acceptable layer method of compaction (Clause 15.2) or minimum test frequencies required to be observed (Appendix A).

4. Technical Note

To facilitate implementation of alternative compaction assessment techniques, a technical note has been prepared to provide a baseline methodology to use LWD as an effective QA tool that can be implemented within earthworks technical specifications. Together with the proposed amendment to MRTS04 presented in Section 3, this technical note provides a valid implementation pathway to allow project-specific implementation on TMR projects.

The note is written to present a methodology to mitigate the perceived additional cost associated with the requirement for continuous parallel testing of DDR with LWD. This is one of the contributing factors which inhibit the potential uptake of on-site modulus-based assessments. The approach taken is to initially define equivalent acceptance 'thresholds' for material acceptance (based on the initial embankment trial that incorporates project, material-specific and test-specific correlations) and then complete regular 're-assessment periods' to re-validate/re-configure the previously defined acceptance thresholds.

The note covers the following key areas:

- Background information – Rationale for why an alternative testing approach is required, and identification of the advantages of moving to a modulus parameter-based specification for earthworks QA testing. This also includes a brief description of the LWD, as well as standard LWD configuration and published test methods.
- Design of LWD technical specification – Presents the important issues to prepare project-specific technical specification for LWD use as an alternative earthwork acceptance tool. An essential part of the technical specification involves the construction of a trial embankment that will reflect the same condition as the production earthworks.
- Trial embankment – A successful trial embankment is needed to establish project and material-specific LWD thresholds. The note specifies detailed requirements such as the minimum number of earthwork layers, the minimum of LWD vs density test pairs, and the maximum time delay between when field moisture, density and LWD measurements are made.
- Interpretation of trial embankment data – Guidance has been provided to undertake single-variable and multi-variate regression analyses to define the relationships between the LWD modulus, density and moisture content dataset. Recommended values of an acceptable correlation relationship expressed as coefficient of determination (R^2) have also been provided.
- Procedure to develop the acceptance threshold value – Where a direct relationship between the LWD-density paired dataset exists, it is a fairly simple procedure to define the acceptance threshold value. However, it is often observed that there is an absence of a direct relationship between LWD-density. When such a scenario occurs, the note provides guidance to derive the acceptance threshold value based on the lot characteristic values. A lower-bound function to the dataset must be fitted to derive a site-specific minimum stiffness (Evd) parameter threshold that would be considered representative for the required density threshold.
- Reporting requirements – To maximise the use of LWD results collected in earthworks, the note presents a list of minimum reporting requirements needed.

A proposed text of the technical note is included in Appendix A of this report.

5. Conclusions

The objective of this project was to seek alternative testing methods to address the limitations of the current methods to assess the quality of earthwork construction, namely the in situ density measurement. The limitations of the current density-based measurements include the long delay between the time of construction and the availability of final test results. Quite often, the previously constructed lots would have been covered up before the final results became available, which leads to costly repair work and delays to the construction program if lower layers were later found to be non-conforming. The second major limitation is the lack of accuracy in the density measurement.

Through a comprehensive five-year study, a number of test methods were identified that can be used to address the limitations identified above. Field trials in New South Wales and Queensland were undertaken to derive a specification to use the LWD as a field tool to rapidly assess lots for conformance. The final research outcomes have been presented this year in the form of proposed amendments to MRTS04, and a technical note that details the technical basis and approach. Throughout the project, several webinars have been presented to disseminate the results and as an avenue to seek industry feedback.

References

Lee, J, Lacey, D & Look, B 2017, 'Best practice in the quality assurance of pavement layers and subgrade: year 1 (2016/2017)', contract report PRP16036, prepared for Queensland Department of Transport and Main Roads under the NACoE program, ARRB, Port Melbourne, Vic.

Lee, J, Lacey, D & Look, B 2019, 'Best practice in the quality assurance of pavement layers and subgrade: year 2 (2017/2018)', contract report PRP16113, prepared for Queensland Department of Transport and Main Roads under the NACoE program, ARRB, Port Melbourne, Vic.

Lee, J, Lacey, D, Look, B & Tarr, K 2020a, 'Best practice in the quality assurance of pavement layers and subgrade: year 3 (2018/2019)', contract report PRP18027, prepared for Queensland Department of Transport and Main Roads under the NACoE program, ARRB, Port Melbourne, Vic.

Lee, J, Lacey, D & Look, B 2020b, 'Best practice in the quality assurance of pavement layers and subgrade: year 4 (2019/2020)', contract report 014925, prepared for Queensland Department of Transport and Main Roads under the NACoE program, ARRB, Port Melbourne, Vic.

Queensland Department of Transport and Main Roads 2020, *General earthworks,* MRTS04, TMR, Brisbane, Qld.

Transport for New South Wales 2020, Earthworks, QA Specification R44, TfNSW, Sydney, NSW.

Appendix A Technical Note

Technical Note TN<XXX>

Guidance on Use of Light Weight Falling Deflectometers (LWDs) to be Accepted as an Alternative Method for Verification of Earthworks Compaction Requirements

Date: June 2021

Queensland Government

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Feedback

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1. Background

The Department of Transport and Main Roads (TMR) is committed to working towards the modernisation of testing procedures for earthworks compaction quality assurance (QA).

Research into the use of modulus-based approaches to earthworks QA has been conducted by TMR, via involvement in National Asset Centre of Excellence (NACOE) projects since 2015. This has been completed alongside industry implementation of similar research, and repeated demonstration of the efficiencies offered by non-density-based measures of earthworks compaction. Both international and domestic research to date has repeatedly demonstrated that the incumbent density testing procedures can be poorly correlated with the material parameters that are used as the basis of design, and the use of alternative methods of in situ earthworks evaluation can provide a direct evaluation of design parameters.

Specifically, TMR has recently (2020) defined testing methodologies associated with light weight deflectometer (LWD) technologies – as detailed in Test Method Q258A and Q258B of TMR's *Material Testing Manual* (MTM). This Technical Note provides further guidance on the key items that would be required to be considered during project-specific LWD verification testing and interpretation (i.e. field trials), such that TMR/Administrators could make an informed decision regarding the suitability of using LWDs to achieve similar compliance outcomes to the traditional (density-based) QA regimes.

The Technical Note is based on the details included in the NACOE P60 project (*Best Practice in Compaction Quality Assurance for Subgrade Materials*) and project-specific Technical Specifications that have been reviewed (and approved LWD use) by TMR Engineering and Technology (E&T).

2. Light Weight Falling Deflectometers (LWDs)

Light weight falling (or portable) deflectometers – also abbreviated as LFWD, LFD, PFWD, or LWD in technical literature – are quasi-static plate load testing apparatus, in which a sliding weight is manually raised up a guide rod and dropped onto a rigid base plate. A load pulse is generated when the weight is dropped on rubber dampers, which passes through the rigid plate and into the ground as a uniform stress. The induced ground deflection under the plate is measured directly via a geophone in contact with the ground surface, or from a velocity transducer/accelerometer embedded in the rigid plate. The key elements of LWD equipment are shown conceptually in Figure 1 (shown as LWD equipment that incorporates a load cell and geophone components).

Note that in this Technical Note, the term LWD is interchangeably used for both true LWDs (those fitted with a load cell) and portable impulse plate load test devices (which are not fitted with load cells and assume an applied test stress). However, the specific proposed LWD for use in any project specification should be clearly identified in any project-specific Technical Specification (refer to Section 4.1).

As a self-contained unit, the LWD is a rapid plate load testing device that provides a stress-deformation response over the duration of the load pulse. Thus, the measurements provided by the LWD can be used to directly assess the composite Young's modulus of the near-surface material condition in the field. A typical test normally consists of a number of repeated weight drops and deflection measurements made from a standardised drop height (in order to standardise the stress adopted for each measurement). The potential non-linearity of the material modulus parameter (e.g. stress-dependency) and the effect of moisture can also affect the returned in situ modulus result.

However, a significant barrier to widespread LWD adoption is the variety of LWDs commercially available within the market, each of which can provide a different in situ modulus parameter – due to the effects of varying configurations and customisations. Variables between LWD brands include the use of different stress states, equipment arrangements and boundary conditions adopted by individual manufacturers. It is also due to this variability between LWD brands that the use of generic or equipment manufacturer's supplied acceptance criteria is not considered sufficient for direct implementation in earthworks QA regimes, and why a quality control validation is required to be undertaken (i.e. field trials that are project and material specific).

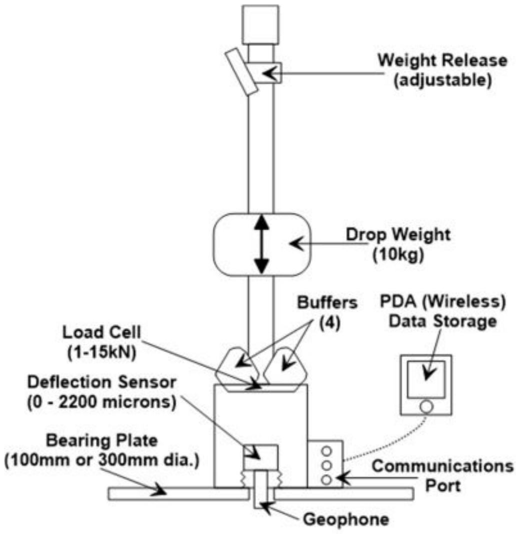

Figure 1 Key elements of light falling weight deflectometer (after Fleming et. al. 2007)

3. Scope of Technical Note

As per the requirements of a universal standard, no preferential selection of any one LWD manufacturer is detailed in this Technical Note. However, by understanding and accounting for the characteristics of the specific LWD and the material being utilised on-site, any LWD can provide a consistent and traceable result which can be readily used for earthworks QA purposes.

Accordingly, the scope of this Technical Note is limited to recommendations relating to specific items that should be addressed by LWD field trials and subsequent interpretation/analysis of data, in order to provide an acceptable project-specific and material-specific Technical Specification for LWD use as an earthworks compaction QA tool.

4. Key Items for Design of LWD Technical Specification

The design of any project-specific Technical Specification for LWD use shall be based on appropriate identification/definition of:

- *Identification of a suitable and standard test method for LWD use* – The LWD Technical Specification shall be sufficient to identify the LWD type and proposed test configuration for QA testing. This should also include the identification of an applicable standard for the on-site test methodology (and any proposed departures from the identified standard).
- *Identify the material type, material quality, range of in situ variables and compaction variables that are to be covered by the LWD test* – This includes appropriate definition of

the source material, construction plant, loose layer thickness, range of moisture condition etc. that is covered by the Technical Specification. The defined ranges shall be sufficient so that the applicability (or otherwise) of the LWD Technical Specification can be readily identified during on-site works.

- *Identification that the acceptance threshold is the equivalent to the existing MRTS04 – General Earthworks specified minimum relative density requirement* – Evidence that the acceptance criteria adopted for use with the LWD results in the appropriate evaluation of achieved in situ compaction, such that there is no additional risk being taken by TMR in terms of the subsequent performance of the earthworks.

4.1 *Defined Standard Configuration and Test Method for LWD Use*

Due to variation in the range of available LWD equipment – in terms of plate size, available drop weights, methods used to measure resulting ground deflections, presence of load cell, buffer arrangements etc. – it is imperative that the LWD utilised for initial material evaluation and derivation of the acceptance thresholds be the same type and configuration as that used for all subsequent in situ LWD testing during production-phase earthworks.

As such, the following variables require definition prior to commencement of trial/production LWD testing:

- *Design pressure (σ_{design})* – Pressure at which the compacted materials will be evaluated, and pressure at which the in situ modulus will be standardised.
- *LWD brand/manufacturer* – Such that the measurement sensors to be utilised and the applicable ASTM (or similar) test methodology can be identified.
- *Plate size, drop weight magnitude, buffer configuration and drop height* – Adopted so the test arrangement routinely can impart the defined design pressure (σ_{design}). Where multiple LWD test arrangements may be available for use – based on the capabilities and calibrated ranges of the LWD test equipment – it is recommended that the arrangement that incorporates the largest possible plate diameter be utilised.

If, for any reason, the defined LWD type or test configuration is required to be altered during the completion of earthworks production, then additional trial embankment testing shall be completed in order that revised E_{LWD} acceptance thresholds can be derived.

Equipment must be calibrated in accordance with manufacturer's requirements.

The above could also largely be defined by identifying the applicable standard for the on-site test methodology, which could include the identification of one of the following:

For LWDs fitted with load cells:

- ASTM E2583-07 (2011). *Standard Test Method for Measuring Deflections with a Light Weight Deflectometer (LWD)*, ASTM International, West Conshohocken, PA
- *Test Method Q258B: Surface Modulus – Light Weight Deflectometer (LWD) – Load Cell Type,* TMR *Materials Testing Manual* (2021)

Examples of LWDs that meet these requirements include the Prima 100 (Sweco), Dynatest 3032 or Terratest 9000 LWD.

For LWDs not fitted with load cells:

- ASTM E2835-11 (2011). *Standard Test Method for Measuring Deflections Using a Portable Impulse Plate Load Test Device*, ASTM International, West Conshohocken, PA
- *Test Method Q258A: Dynamic Modulus of Deformation – Light Falling Weight Device – Accelerometer Type*, TMR *Materials Testing Manual* (2021)

Examples of LWDs that meet these requirements include the Zorn ZFG 3000, HMOP LFG, Terratest 4000/5000 and Olsen LWD-1.

4.2 *Identification of Material Quality, In Situ Material Variables and Compaction Variables*

The production earthworks LWD Technical Specification – that is also required to be reflected in site-specific and material-specific LWD trials – shall include clear definition of the following:

- *Material quality* – Such that the characteristics of the source material can be identified (and applicable bounding parameters identified).
- *Construction plant* – The same plant shall be used for compaction of trial embankment materials as with use in production earthworks.
- *Loose layer thickness* – The nominated loose layer thickness for production earthworks shall be adopted for the LWD trials.
- *Moisture condition* – The same moisture conditioning techniques proposed to be utilised in earthworks production shall be adopted for the LWD trials (and applicable bounding parameters identified).
- *Poisson's ratio* – The Poisson's ratio (υ) to be consistently applied for the transformation between in situ measurements (stress, deformation) and in situ modulus (E) shall be defined and appropriate for the material being assessed.
- *Identification of existing specifications/other requirements* – Any minimum and/or characteristic value of design parameters (e.g. modulus, bearing capacity) or compaction level (e.g. density ratio) that are currently required to be verified by the QA regime being applied to the compacted earthworks shall be identified.

5. Minimum Requirements for Field Trials for LWD Use as Earthworks Compaction Tool

5.1 *Trial Embankment (Compacted Earthworks)*

A trial embankment shall be constructed utilising the source materials and compaction characteristics as proposed to be utilised for the earthworks production methodology. A minimum of two (2) layers of earthworks – adopting the identified loose layer thickness – shall be constructed, such that the second layer is compacted directly upon the first. It is thus expected that the minimum (loose layer) thickness of the trial embankment would exceed 600 mm (i.e. two (2) x 300 mm loose layer thickness lifts).

During the construction of the trial area, the source materials shall be handled as close as possible to the method proposed to be used for sourcing of materials during the earthworks production phase.

A ramp/approach area shall be constructed to allow the construction plant to accelerate to proposed production speed prior to entering the trial area. This ramp/approach area shall not be considered to form part of the trial embankment. With the exclusion of the ramp/approach area, a trial embankment would be expected to have minimum dimensions of 40 m (length) and be in excess of 4.2 m wide (i.e. two (2) times roller drum width plus allowance such that the plant does not work at the crest of the batter slope).

For clarity, a separate trial embankment shall be prepared for each moisture condition and/or source material to be assessed by LWD testing.

5.2 *Trial Embankment – Side-by-side LWD and Density Testing*

A minimum of 15 LWD and density test pairs shall be completed on the compacted surface of the trial embankment prepared area, with test sites selected in a random and unbiased manner, and away from the compaction plant's acceleration zone.

LWD testing of the prepared (compacted) trial embankment surface shall be undertaken via the adoption of the specified standard test methodology (refer to Section 4.1), which shall be a standard applicable to the LWD type being evaluated and shall result in the defined σ_{design} magnitude being achieved with each weight drop. All LWDs shall be calibrated in accordance with manufacturer and applicable standard requirements.

Density testing shall be undertaken in accordance with the requirements of MRTS04 – *General Earthworks* and each test site shall be sampled and the in situ field moisture content (FMC) determined.

All side-by-side testing (paired LWD and density) shall be performed within two (2) hours of the completion of compactive efforts, such that the effect of surface drying on the measured data is minimised. In addition, it is recommended that paired LWD and density tests shall be completed within 30 minutes of each other, such that the moisture condition during the completion of both test types is maintained.

All testing undertaken at a specific test site shall be undertaken at a distance no greater than 500 mm offset from the outer edge of the LWD testing completed.

6. *Interpretation and Reporting*

The data applicable to each test site – and thus each material type and moisture condition – shall initially be aggregated into a single dataset, with the following results identified as a minimum for each test site:

- density (density ratio, wet/dry density)
- in situ, LWD measured modulus [E_{LWD} or E_{vd} , at design pressure, σ_{design}])
- in situ moisture content at time of testing (e.g. field moisture content, FMC or moisture ratio, MR).

Based on this data aggregation, the range of both the density and moisture content of the in situ testing of the prepared trial embankment shall be defined. These ranges become the outer limiting bounds for the validity of any derived LWD Technical Specification (and may be further refined based on the identification of any outliers/non-consistent data trends).

6.1 *Evaluation of Variation of In Situ Modulus (E_{LWD} or E_{vd}) within Materials*

The average (μ), standard deviation (σ) and coefficient of variation (CoV) of the calculated E_{LWD} or E_{vd} parameters shall be completed for the trial embankment dataset (i.e. uniform material condition).

Typical CoV values determined for various material classification categories are detailed in Table 1. If the CoV values of the LWD datasets are calculated to be above the applicable range identified in Table 1, this may be indicative of a non-consistent compaction state being achieved on-site. Observance of excessive CoV values (beyond the upper limits identified in Table 1) shall trigger a review of the data and material source in order to ascertain the reason for such variation.

Table 1 Typical coefficient of variation (CoV) of in situ LWD modulus parameters – by material type

Material type	Typical coefficient of variation (CoV) of E_{LWD} or E_{vd}
GRAVEL dominated materials	10 – 20 %
SAND dominated materials	15 – 35 %
FINES dominated materials	30 – 60 %

6.2 *Evaluation of Moisture-dependent Behaviour of Density or In Situ Modulus Parameter*

Both single-variable and multi-variate regression analyses (adopting both linear and non-linear functions) shall be completed to evaluate the effect the moisture content of the compacted material has on the achieved density ratio (DR or wet/dry density), the in situ LWD measured modulus (E_{LWD} or E_{vd}) and/or the relationship between all three (3) variables.

The results of these single-variable and multi-variate regression analyses should be considered in terms of (i) the correlation co-efficient (R^2); and (ii) the statistical significance (p) of the defined relationship. As general guidelines, the following recommendations are made:

- The minimum correlation co-efficient strength threshold typically applied to earthworks-related data is $R^2 > 0.5$ (e.g. as per Highways England 2009; ISSMGE 2005). A value in excess of this should be identified to determine a direct (1:1) relationship between density test results and in situ LWD measured modulus.
- A 95% confidence level (i.e. $\alpha < 0.05$) should be achieved for a relationship to be considered statistically significant.
- If the single-variable relationship of best fit between moisture content and another parameter achieves a coefficient of determination (R^2) of, or in excess of 0.3, and a 95% confidence level (i.e. $\alpha < 0.05$), then the material shall be considered moisture dependent for the purposes of assessment. Otherwise, the material shall be considered non-moisture-dependent".

The Technical Specification shall clearly identify any defined relationships between the modulus of the LWD, density, moisture content dataset, including the identification of the correlation co-efficient (R^2) and confidence level (significance, p).

An example of a dataset is provided in Figure 2 that shows a good, direct correlation between LWD results (used to "predicted" equivaled density ratio, DR), and the results of traditional density tests (Reported DR in the figure) .

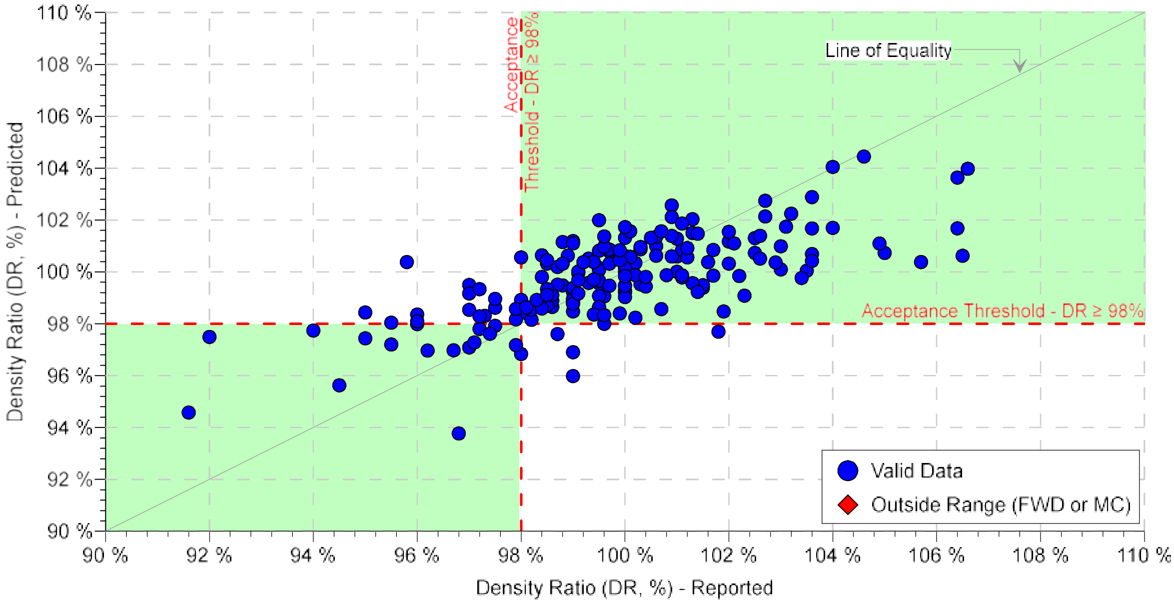

Figure 2 Example of well correlated paired (side-by-side testing) density ratio (DR, % — horizontal axis) and in situ modulus (used to 'predict' equivalent DR, % — vertical axis)

6.3 *Derivation of Acceptance Threshold Values Applicable to the E_{LWD} or E_{vd} Parameter*

The derivation of LWD acceptance thresholds that reflect the existing (density) requirements included in *MRTS04 – General Earthworks* shall be calculated by use of the defined LWD-density-moisture content relationships derived in Section 6.2.

Note, it is often observed that there is an absence of the definition of a direct relationship between the LWD-density paired dataset (i.e. no relationship when tests are considered on a 1:1 basis). This result is consistent with previous Australian research of granular materials used in infrastructure earthworks (e.g. Lee et. al. 2017, 2019, 2020a, 2020b), and is considered to demonstrate that different variables influence the result of each specific test technique (i.e. the density ratio does not directly measure/reflect in situ stiffness of the compacted materials). An example of a material dataset that shows a poor 1:1 correlation between LWD and density ratio results~~,~~ is shown in Figure 3.

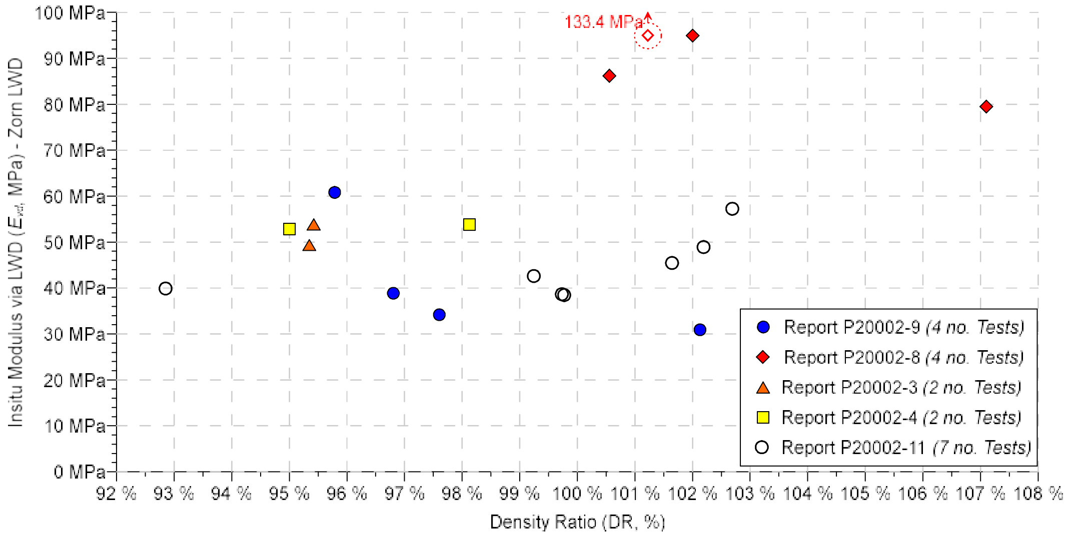

Figure 3 Example of poorly correlated paired (side-by-side testing) density ratio (DR, %) and in situ modulus (E_{vd}, MPa) parameters

Based on the absence of a definable relationship when the dataset is considered as individual data-pairs (E_{vd} and DR) or data-triplets (E_{vd}, FMC and DR), it is considered acceptable that the dataset be instead evaluated by lot characteristic values. A lower bound function to the LWD/DR lot-based dataset shall be fitted in order to initially derive site-specific minimum E_{vd} parameter thresholds that would be considered approximate representations for the required density thresholds (e.g. DR ≥ 95%, ≥ 97%, ≥ 98% and/or ≥ 100%).

Any derived in situ modulus (E_{LWD} or E_{vd}) acceptance thresholds equivalent to DR ≥ 95%, 97%, 98% and 100% shall be clearly defined and plotted against the available dataset. The available dataset shall also be fully evaluated against the defined acceptance thresholds, and the rate of 'matching' test data (e.g. PASS from the density test and PASS from the LWD test) shall be calculated. Where disparity occurs between test pairs (e.g. PASS from the density test and FAIL from the LWD test) then the split between the test type shall also be determined and reported (e.g. the frequency of such a disparity in the results in the LWD test demonstrating acceptance compared to the frequency of such a disparity in the results in the density test demonstrating acceptance). The frequency and nature of such 'mismatches' should be compared against the risk share associated with the existing QA regime (density) included in MRTS04 – *General Earthworks*, and checked for bias towards the client or contractor.

A summary of the key points to be followed when deriving the acceptance threshold values applicable to the E_{LWD} or E_{vd} parameter is presented as a flow chart in Figure 4.

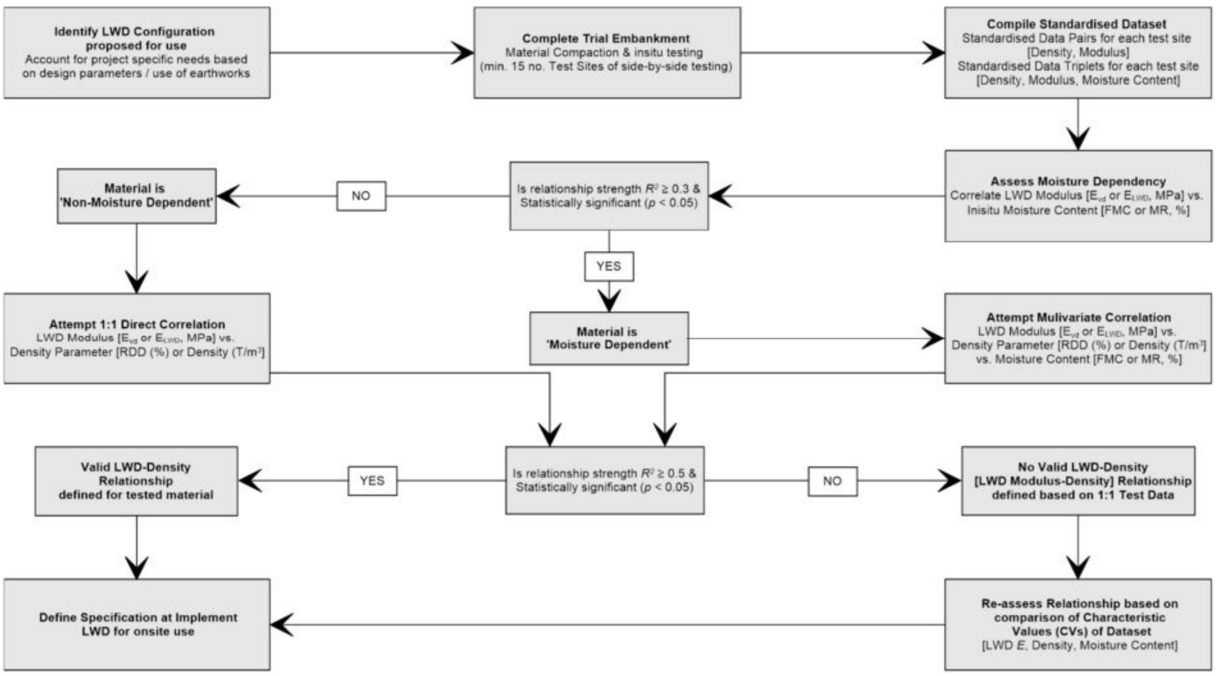

Figure 4 Flow chart showing key steps for assessment/derivation of equivalent acceptance thresholds for LWD use (in lieu of traditional (density) testing minimum thresholds included in MRTS04 – *General Earthworks*)

6.4 *Reporting/Technical Specification for LWD Testing*

The project-specific Technical Specification for LWD testing shall identify all requirements that the LWD testing shall be completed under. This includes a clear summary of:

- LWD standard configuration and operation *(refer to Section 4.1)*
- definition of the earthworks (FILL) material and the ranges of density (and thus modulus) and moisture content over which the Technical Specification is to be considered valid *(refer to Sections 4.2 and 6.0)*
- designation of the earthworks (FILL) material as either moisture dependent or non-moisture-dependent *(as evaluated by single and multi-variate analyses of the trial embankment dataset, as in Section 6.2)*
- minimum in situ modulus values (E_{LWD} or E_{VD}) to be used in lieu of/equivalent to density ratio (DR) thresholds *(as derived in Sections 6.2 and 6.3*)
- method of LWD modulus evaluation for an earthworks lot (e.g. no test shall fall below minimum identified E_{LWD} or E_{VD} values, or use of evaluation via characteristic values for a lot)
- minimum LWD test frequency
- proposed method for in situ moisture content determination requirements for ongoing use of LWD (if required)
- minimum frequency for derived relationships to be re-evaluated during earthworks production (either in the maximum timeframe prior to re-evaluation or the maximum earthworks volume prior to re-evaluation). This would take the form of side-by-side tests (density and LWD) at an agreed specified frequency/volume of FILL placement, and an ongoing monitoring of the relationships derived for the site/materials.

7. Implementation of LWDs in Production Earthworks

It has been found that easy implementation of TMR-accepted LWD-based test assessment regimes can be achieved by defining a flow chart and providing on-site personnel with an appropriate calculator (e.g. tablet-supported spreadsheet calculator). This results in quick field assessment of each test site once the required test parameters have been determined (E_{vd} from LWD, and potential moisture content data). The limits of applicability of each parameter and derived relationships can be quickly updated into the provided field calculator, such that ‘live’ updating to the alternative testing regime can also be achieved.