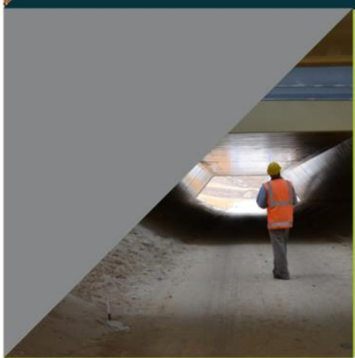
WARRIP

WESTERN AUSTRALIAN ROAD RESEARCH AND INNOVATION PROGRAM

Review of Density Compliance Systems for Subgrade and Embankment Construction - Stage 1



LINCOLN LATTER, ZIA RICE & BOB ANDREWS

AN INITIATIVE BY:

THE GOVERNMENT OF WESTERN AUSTRALIA

mainroads WESTERN AUSTRALIA

arrb

a

Review of Density Compliance Systems for Subgrade and Embankment Construction - Stage 1

for Main Roads Western Australia

ABN 68 004 620 651

Victoria
80A Turner Street
Port Melbourne VIC 3207
Australia
P: +61 3 9881 1555
F: +61 3 9887 8104
arrb.vic@arrb.com.au

Western Australia
191 Carr Place
Leederville WA 6007
Australia
P: +61 8 9227 3000
F: +61 8 9227 3030
arrb.wa@arrb.com.au

New South Wales
2-14 Mountain Street
Ultimo NSW 2007
Australia
P: +61 2 9282 4444
F: +61 2 9280 4430
arrb.nsw@arrb.com.au

Queensland
21 McLachlan Street
Fortitude Valley QLD 4006
Australia
P: +61 7 3260 3500
F: +61 7 3862 4699
arrb.qld@arrb.com.au

South Australia
Rundle Mall
Adelaide SA 5000
Australia
P: +61 8 7200 2659
F: +61 8 8223 7406
arrb.sa@arrb.com.au

	Reviewed
Project Leader	Zia Rice
Quality Manager	Bob Andrews

PRP17049
2018-003
July 2019

SUMMARY

The monitoring of the degree of compaction obtained in the field by Main Roads Western Australia (MRWA) is typically conducted using the dry density ratio test (MRWA test method WA 134.1). This test requires the dry density of the compacted in situ material to be determined by measuring both the moisture content and wet density then comparing it with the maximum dry density (MDD) determined at optimum moisture content (OMC) from a standard laboratory compaction test using a known compactive effort and moisture content (MRWA test methods WA 133.1 and WA 133.2).

The current density compliance processes for subgrade and embankment construction (earthworks) employed by MRWA have operational limitations, require destructive testing of the compacted material and it can be difficult to obtain repeatable results.

As a result, MRWA commissioned ARRB to review aspects of the MRWA density compliance processes for the compaction of subgrades and embankments detailed in MRWA Specification 302 *Earthworks* and Specification 501 *Pavements*.

A national and international review was undertaken with a view to:

- Identify the applicability of alternative equipment and methodologies to the current nuclear density meter (NDM) for the determination of field compaction.
- Identify alternative non-destructive methodologies for the determination of 'dry-back' moisture content.
- Provide guidance for the use of the Perth Sand Penetrometer in contractor-developed compaction method specifications.
- Review the application of dry density ratio and alternate methodologies as they apply to compaction compliance of non-cohesive subgrade and embankment materials.
- Review intelligent compaction technologies which are able to accurately record and document compaction processes for quality control purposes.

As a result of the review the following has been recommended:

- Undertake a field trial to determine whether the Light Falling Weight Deflectometer can be used as a non-nuclear alternative to the NDM or the sand replacement test for measuring the in situ density of soils. Other selected devices that could be examined in the trial include the dynamic cone penetrometer, static plate load tester, Clegg Hammer and soil density gauge.
- Undertake a field trial to investigate the potential use of the NDM as a non-destructive alternative to the convection oven method in terms of measuring moisture content.
- Trial the PSP framework proposed in this report is trialled during future construction projects to determine its suitability and applicability for practical use and to determine whether or not it improves the quality of the Perth Sand Penetrometer method specification submissions.

- Findings from the literature review do not support the immediate adoption of the density index method for cohesionless soils unless laboratory evaluations are undertaken to determine the repeatability of test results.
- The review of intelligent compaction literature suggests that MRWA should consider undertaking trials with intelligent compaction technologies to identify the accuracy of the data reported during the compaction process. This work could form a part of the overall field trial.

CONTENTS

TABLES

FIGURES

GLOSSARY OF ABBREVIATIONS

Abbreviation	Definition
AASHTO	American Association of State Highway and Transportation Officials
AS	Australian Standard
ASTM	American Society of Testing and Materials
BCD	Briaud Compaction Device
bgl	below ground level
CBR	California Bearing Ratio
CHM	Clegg Hammer Modulus
CIV	Clegg Impact Value
DCP	Dynamic Cone Penetrometer
DPU	Diesel Platen Universell (reversible diesel plate compactor)
EDG	Electrical Density Gauge
FHWA	Federal Highway Administration (US)
GADOT	Georgia Department of Transportation
GPS	Global Positioning System
HMA	Hotmix asphalt
IADOT	Iowa Department of Transportation
IC	Intelligent compaction
ICMV	Intelligent compaction measurement values
INDOT	Indiana Department of Transportation
KTC	Kentucky Transport Cabinet
LFWD	Light Falling Weight Deflectometer
MC	Moisture content
MDD	Maximum dry density
MDI	Moisture-density indicator
MDI	Moisture density indicator
MIDOT	Michigan Department of Transportation
MMDD	Modified maximum dry density
MnDOT	Minnesota Department of Transportation
MRWA	Main Roads Western Australia
MSE	mechanically-stabilised earth
NCDOT	North Carolina Department of Transportation
NDM	Nuclear Density Meter
OMC	Optimum Moisture Content
PDA	Personal Digital Assistant
PLT	Plate Load Test
PR	Penetration resistance
PSD	Particle Size Distribution
PSP	Perth sand penetrometer
PSPA	Portable Seismic Pavement Analyser
PSPA	Portable Seismic Pavement Analyser
QA	Quality Assurance
QC	Quality Control
RTK	Real-time Kinematic
SDG	Soil Density Gauge

Abbreviation	Definition
SDG	Soil Density Gauge
TDR	Time Domain Reflectometry
TMR	Queensland Department of Transport and Main Roads
TxDOT	Texas Department of Transportation
UTC	Coordinated Universal Time
UTM	Universal Transverse Mercator
VRS	Virtual Reference Stations
VTrans	Vermont Agency of Transportation

1 INTRODUCTION

1.1 Background

Compaction of subgrade soils and embankments (earthworks) is used to optimise the bearing capacity of a material and decrease permeability (ingress of water) which may weaken the bearing strength upon which a road pavement is constructed.

The monitoring of the degree of compaction obtained in the field by Main Roads Western Australia (MRWA) is typically conducted using the dry density ratio test (MRWA test method WA 134.1 (Main Roads Western Australia 2012a). This test requires the dry density of the compacted in situ material to be determined by measuring both the moisture content and wet density then comparing it with the maximum dry density (MDD) determined at optimum moisture content (OMC) from a standard laboratory compaction test using a known compactive effort and moisture content (MRWA test methods WA 133.1 (Main Roads Western Australia 2017) and WA 133.2 (Main Roads Western Australia 2012b)).

The current density compliance processes for subgrade and embankment construction (earthworks) employed by MRWA have operational limitations, require destructive testing of the compacted material and it can be difficult to obtain repeatable results.

As a result, MRWA commissioned ARRB to review aspects of the MRWA density compliance processes for the compaction of subgrades and embankments detailed in MRWA Specification 302 (Main Roads Western Australia 2015) *Earthworks* and Specification 501 *Pavements*.(Main Roads Western Australia 2018a).

1.2 Purpose

The purpose of the project was to review current practices, both nationally and internationally, in relation to several aspects of subgrade and embankment construction with the intention of identifying areas for improvement within the current density compliance process, and the implications of employing the new techniques. The areas identified for review were as follows:

- Identify the applicability of alternative methods to the Nuclear Density Meter (NDM) for the determination of the field density of fine-grained soils typical of those specified for embankment fill or subgrade application.
- Identify non-destructive methods for the assessment of the moisture content of soils required to achieve dry-back prior to the placement of overlying layers.
- Provide guidance for the development of project-specific method specifications incorporating the Perth Sand Penetrometer (PSP).
- Evaluate the use of the Maximum and Minimum Density Index as an alternative to the MDD for subgrade and embankment compaction specifications.
- Investigate the potential use of intelligent compaction systems as an alternative quality control (QC) method.

Furthermore the project was to identify alternative methods that have shown possible practical application and merit further investigation in future stages of the project.

1.3 Benefits

The anticipated benefits to MRWA as a result of this review were as follows:

- A ranking of alternative density methods which are applicable to sands and which are quick, accurate, non-destructive, environmentally friendly, and do not have strict safety requirements like the NDM. This would help guide future investigations in this space if deemed warranted by MRWA.
- The adoption of a non-destructive method for measuring density and dry-back would result in increased efficiency through the minimisation of reinstatement requirements.
- A draft framework to assist in the development of project-specific PSP method specifications, resulting in more efficient work processes and on-site testing protocols.
- The adoption of maximum and minimum density rather than MDD and OMC would result in an improvement in the current MRWA compaction specification for sands.
- The successful outcome of the project would lead to increased awareness and understanding by MRWA laboratory staff of the applicability of these test methods to the fundamental mechanisms of material behaviour, including the advantages and disadvantages of test methods and compliance systems for use with sand subgrades and embankments.
- A reduction in the need for surveillance officers to attend all sites.
- More in-depth documentation of QC data for soil compaction works.

1.4 Approach

The objective taken in the review of the various aspects related to MRWA compaction density compliance processes for subgrade and embankment construction was as follows:

- Conduct a literature review of nuclear density alternatives for the determination of field density and moisture content – Section 2.
- Summarise MRWA's current dry-back compliance method and review alternative, non-destructive methods– Section 3.
- Review the current Perth Sand Penetrometer test method, including case studies of past method specification submissions to MRWA, and suggest guidelines for the development of project-specific Perth Sand Penetrometer method specifications – Section 4.
- Review the density characterisation of non-cohesive subgrade and embankment fill used by MRWA – Section 5.
- Implementation of intelligent compaction technology to allow in-depth documentation of QC data relating to compaction works – Section 6
- Summarise the review, including recommendations for further investigation by MRWA in terms of their appropriateness and practicality – Section 7.

2 ALTERNATIVES FOR COMPACTION QA/QC OF SAND SUBGRADES AND EMBANKMENTS

2.1 Introduction

As a part of earthworks construction quality assurance (QA) management, the NDM has a proven track record as a QC tool for assessing the in situ density of a wide range of soil types. However, the NDM comes with a critical limitation: the live nuclear isotope used for the test and the hazards it presents to both the environment and the operators (Nazzal 2014).

As a result, there is strict safety and operational restrictions on its use and regulatory operator training and proficiency standards are placed on its use to limit accidental and avoidable radiation exposure. These strict requirements add extra cost and time associated with an otherwise relatively quick and straightforward test. Alternative volume replacement methods, such as the sand replacement, rubber balloon and the fixed volume extractive tests, are time-consuming and destructive. Therefore, there is a preference to shift to non-nuclear methods of QA/QC testing which involve the use of minimal equipment, are less destructive and easily repeatable.

2.2 Current In situ Density QA/QC Methods

Traditional QC methods used for QA of in situ-compacted material within Australia include the NDM and various volume replacement methods such as the sand replacement test and the fixed volume extractive method as just discussed.

The standard test procedures required by Australian and New Zealand road authorities for these three common methods are detailed in Table 2.1.

Table 2.1: Summary of current compaction QA/QC methods within Australia and New Zealand

Road Authority	Specification	Allowed test	Test comments	Standard test procedure
Department of Planning, Transport and Infrastructure, SA	Specification: Part R10 *Construction of Earthworks*(1)	Nuclear gauge	N/A	AS 1289.5.8.1
Queensland Department of Transport and Main Roads	Technical Specification: MRTS04 *Earthworks*(2)	Relative compaction*	For cohesive materials	Q140A
		Density index	For cohesionless materials	AS 1289.5.5.1 or AS 1289.5.6.1
Main Roads Western Australia, WA	Specification 201: *Quality Systems*(3)	Nuclear gauge	If in situ density is within the range of densities of 1.5–3.05 t/m^3	WA 324.1
		Sand replacement	If in situ density is outside the range of densities of 1.5–3.05 t/m^3	WA 324.2
Roads and Maritime Services, NSW/ACT	QA Specification R44, *Earthworks*(4)	Nuclear gauge	≤ 20% by mass retained on 37.5 mm AS sieve	T173
		Sand replacement	As above in addition to > 20%, ≤ 40% by mass retained on 37.5 mm AS sieve	T119
		Fixed volume extractive method	Fine- to medium-grained cohesionless materials, including one size or gap-graded	T165
VicRoads, Vic	*Code of Practice: Acceptance of Field Compaction*, RC 500.05(5)	Nuclear gauge	Not to be used with materials with > 20% by mass retained on 37.5 mm AS sieve	AS 1289.5.8.1
Department of State Growth, Tas	Roadworks Specification R22 *Earthworks*(6)	Nuclear gauge	N/A	AS 1289.5.8.1
		Sand replacement		AS 1289.5.3.1 or AS 1289.5.3.2
Department of Infrastructure, Planning and Logistics, NT	Standard Specification for Roadworks(7)	Nuclear gauge	N/A	NTP 102.1 and AS 1289.5.8.1
New Zealand Transport Agency, NZ	*Specification for Construction of Unbound Granular Pavement Layers*, TNZ B/02:2005(8)	Nuclear gauge	N/A	NZS 4407 test method 4.2 or 4.3
		Sand replacement		NZS 4407 test method 4.1

* Note: In October 2014 TMR removed references to the sand replacement method for density testing and replaced it with the relative compaction test (TMR 2018b).

Source:
1 DPTL (2017).
2 TMR (2018a).
3 Main Roads Western Australia (2018b).
4 RMS (2012).
5 VicRoads (2017).
6 DOSG (2012).
7 DIPL (2017).
8 TNZ (2005) and Standards New Zealand (2015).

2.3 Current MRWA Methods and Compaction Requirements

To ensure density conformance is achieved within earthworks layers, Clause 1.1.1 of the MRWA *Specification 201: Quality Systems* (Main Roads Western Australia 2018b) details that density is to be measured using the NDM in accordance with MRWA test method WA 324.2 (Main Roads Western Australia 2013a), unless the in situ densities are outside the range of 1.5 – 3.05 t/m^3, in which case the sand replacement method in accordance with MRWA test method 324.1 is to be applied.

The MRWA compaction requirements and methods for subgrades and embankments are described in *Specification 302 Earthworks* (Main Roads Western Australia 2015). The compaction requirements are based upon the characteristic dry density ratio of the soil, as summarised in Table 2.2. The MDD is determined in the laboratory using modified compactive effort in accordance with WA 133.1 (Main Roads Western Australia 2017) for fine- and medium-grained soils or WA 133.2 (Main Roads Western Australia 2012a) for coarse-grained soils.

Engineering Road Note (ERN) 8 (Main Roads Western Australia 2008) recommends at least six tests per lot are carried out for subgrades and embankments.

Table 2.2: MRWA typical earthworks compaction requirements

Earthworks element	Characteristics dry density ratio (%)	
	Perth sands	Other materials
Embankment foundation	90	88
Embankment construction	95	90
Subgrade preparation	96	92

Source: MRWA (2015).

2.3.1 Sand Cone/Replacement Test

The sand replacement test, in accordance with WA 324.1, is conducted by excavating a hole of approximate cylindrical shape from the surface of the compacted soil. The volume of the hole is determined by filling the hole with a clean, uniform sand of known density. The mass and moisture content of the excavated soil is then determined in the laboratory in accordance with MRWA Test Method WA 110.1 *Convection Oven Method* (Main Roads Western Australia 2011a) or WA 110.2 *Microwave Oven Method* (Main Roads Western Australia 2011b) as appropriate. The dry density is then calculated using Equation 1.

$$\rho_d = \frac{m_d - m_s}{V_G - V_S} \qquad (1)$$

where

ρ_d = dry density (t/m^3)

m_d = mass of dry soil excavated from hole (g)

m_s = mass of material greater than 19.0 mm (g)

V_G = gross volume of hole (cm^3)

V_S = volume of material greater than 19.0 mm (cm^3)

2.3.2 Nuclear Density Method

MRWA Test Method WA 324.2 describes the procedure for the in situ determination of the dry density of materials with less than 20% retained on the 37.5 mm sieve by the use of a NDM in direct transmission mode.

The test is carried out by driving a rod or drilling a hole at least 50 mm into the soil and placing the NDM on the surface of the material. The NDM probe is then inserted into the pre-drilled hole and gamma radiation is emitted from the device through the material to the sensor, providing an average density measure of the material between the two points. This process can measure up to depths of approximately 300 mm.

NDMs also have the capability to determine the in situ moisture content of compacted soils. The moisture measurement is undertaken in "backscatter" mode where the source is located within the body of the NDM. It has a maximum measuring penetration of no more than 75 mm (approx.) below the surface. Specification 201 states that the moisture content shall only be determined using the NDM in accordance with WA 324.2 if it is not practicable to use WA 110.1. Determining the moisture content of soil using the NDM is further discussed in Section 3.1.1.

NDMs used for testing in accordance with MRWA specifications are required to be calibrated using WA 135.1 *Calibration of Nuclear/Moisture Density Meters: Standard Blocks* (Main Roads Western Australia 2014). Furthermore, due to the presence of radioactive materials within the device, the purchase, use, maintenance, transport and storage of NDMs is heavily regulated by legislation in Australia. A license is required to purchase and operate NDMs, and ongoing monitoring of personnel operating these devices is also required to prevent risks to human safety (ARPANSA 2004).

2.4 Non-nuclear Alternatives for Density QA/QC

Non-nuclear methods for assessing the in situ field density for QA/QC can be divided into the following categories:

- volume replacement methods:
  - the estimation of dry density by filling an excavated hole with material which has a predetermined density.
- penetration test devices:
  - in situ strength assessment techniques that utilise pressure applied to the surface of the soil to measure the resistance of the soil to penetration. High applied pressure and lower penetration rates are attributed to higher field density.
- surface-based impact devices:
  - devices that apply static, vibratory or impact loads and estimate material stiffness based on the load and displacement measurements. Higher stiffness is attributed to higher field density.
- electrical moisture-density devices:
  - devices that attempt to relate the electrical properties of the soil to the dry unit weight and moisture content of the soil.
- geophysical methods:
  - devices that generate and detect surface waves in the tested layer to determine the soil modulus. Higher moduli are attributed to higher field density.
- in situ (sacrificial) sensors:
  - equipment buried within the compacted soil to monitor the increase in the amplitude of compression waves during compaction and changes in material density.

A summary of non-nuclear alternatives for field density QA/QC which were assessed for this review are presented in Table 2.3 in addition to the various standard test procedures (where applicable). Each method is discussed further in the following sections.

As literature regarding the sacrificial sensor method was very limited, it was not reviewed as part of this study.

Table 2.3: Summary of non-nuclear field density QA/QC methods

Category	QA/QC method	Description	Test method
Volume replacement methods	Sand cone/ replacement	A hole of specific dimensions is excavated from the surface and the mass and moisture content of the recovered soil is measured in the laboratory. The volume of the hole is determined by full replacement of the excavation with a clean, uniform soil of known density.	▪ AS 1289.5.3.1 ▪ AS 1289.5.3.2 ▪ WA 324.2 ▪ ASTM D1556 / D1556M-15e1
	Rubber balloon density	A quantity of compacted soil is removed and weighed, while the volume of the excavated hole is found by measuring the volume of water in a rubber balloon, required to fill the excavated hole.	▪ ASTM D2167
	Steel shot	Similar to the above methods. Density is determined by excavating a hole in the soil. The hole is filled with steel shot which has a pre-determined bulk density and the volume of the shot used to fill the hole is measured and used to estimate wet density.	▪ N/A
Penetration test	Dynamic cone penetrometer (DCP)	A hand-operated device for measuring the resistance of the compacted soil to penetration by a steel cone. The steel cone is connected to a rod and driven into the ground by a 9 kg drop hammer. From this test, the field California Bearing Ratio (CBR) and allowable bearing capacity can be estimated.	▪ AS 1289.6.3.2 ▪ Q114B ▪ ASTM D6951 / D6951M-18
	PANDA probe	A device that determines the cone tip resistance by measuring the driving energy and penetration rate after each hammer blow. Similar to the DCP, the cone tip resistance can be used to infer density, or derive material properties such as shear strength, in situ CBR or modulus values.	▪ NF P 94-105
	Borehole shear tester	An in situ shearing device that measures the drained shear strength under different normal stresses. The operation has two phases: the consolidation phase and the shearing phase. A Mohr-Coulomb failure plane can be plotted and drained shear strength parameters for cohesion (c) and angle of friction (Φ) can be calculated.	▪ N/A
Surface-based impact devices	Static plate load test	Composite elastic modulus (E) values are determined by measuring the average settlement of a rigid plate under known loadings. Usually, multiple loading and unloading cycles are applied to determine the initial and reloading responses. Historically, this method has been used as the reference standard for determining the stiffness/modulus in the field. The main limitation is the size of the plate and the high setup and running costs.	▪ ASTM D1195 / D1195M-09(2015) ▪ ASTM D1196 /D1196M-12(2016)
	Light Falling Weight Deflectometer (LFWD)	The LFWD measures the deflection induced in the pavement by a circular loading plate under a dropped weight. A composite elastic modulus can be determined based on the measured force and pavement deflection under the loading plate. The capability of the equipment varies with different manufacturers. Some models include built-in load cells.	▪ ASTM E2583 ▪ ASTM E2835
	Clegg Hammer	The Clegg Hammer test involves the dropping of a weight directly onto the surface of the pavement. The stiffness and modulus of the tested area is inferred by measuring the deceleration of the instrumented hammer.	▪ AS 1289.6.9.1 ▪ ASTM D5874
	Briaud compaction device (BCD)	The BCD utilises a surface base plate that is in contact with the surface. The BCD measures the bending strain, from which the stiffness of the soil is then calculated.	▪ N/A
	GeoGauge	The GeoGauge measures the deflection of a soil by applying a vibratory force at different frequencies and measures the deflection of a plate. Its small size and portability makes it an ideal QA device during earthworks construction. However, it only has a limited depth of influence (to about 300 mm).	▪ ASTM D6758
Electrical moisture-density devices	Moisture-density indicator (MDI)	The MDI uses time domain reflectometry (TDR) to determine the wet density and moisture content of a material. This is achieved by generating an electro-magnetic pulse through four metal spikes driven into the test material. The voltage signal returned is analysed by software to estimate soil wet density and moisture content.	▪ ASTM D6780 / D6780M-12
	Electrical density gauge (EDG)	The EDG uses high radio frequency energy transmitted into the material to measure the density and moisture content through tapered darts driven into the soil in a specific geometry.	▪ ASTM D7698

Category	QA/QC method	Description	Test method
	Soil density gauge (SDG)	By using an advanced electrical impedance spectroscopy, the SDG allows for non-contact measurements of soil density and moisture content. The compaction level is measured by the changes in electrical impedance of the material matrix. A known moisture and density reading on the soil of interest is required to calibrate the density and moisture content.	▪ ASTM D7830 / D7830M-14
Geophysical methods	Portable seismic pavement analyser (PSPA)	Used to estimate the seismic modulus of the pavement structure based on its response to seismic excitation. They could be used to derive the shear wave velocity properties of the compacted material in the embankment.	▪ N/A

Source: adapted from Lee et al. (2017, p. 3).

2.4.1 Volume Replacement Methods

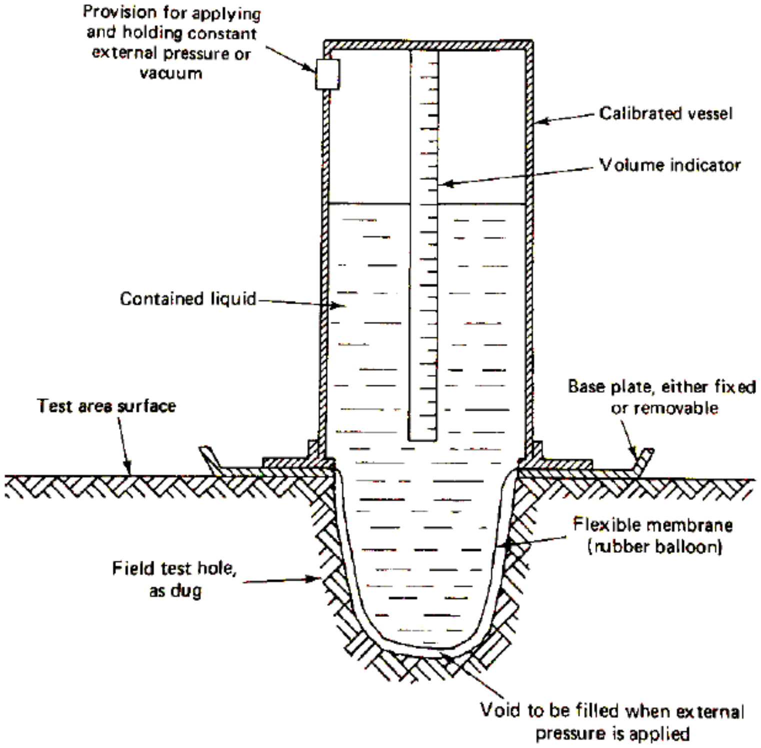
Rubber balloon method

The rubber balloon density test is a volume replacement method that determines the wet density of a soil. It is conducted in accordance with ASTM D2167 *Standard Test Method for Density and Unit Weight of Soil in Place by the Rubber Balloon Method.*

This test involves excavating a test hole in the compacted soil, weighing the excavated soil and measuring the volume of the hole by inflating a balloon in the hole, typically with water, and measuring the volume of water required to inflate the balloon in the hole. The total unit weight is calculated by dividing the total weight of soil excavated from the hole by the volume of the hole. The dry unit weight and moisture content of the soil are determined using the convection oven or microwave oven method (described in Section 3) (Rathje et al. 2006).

The apparatus consists of a metal base plate with a 100 mm diameter hole in the centre and a water-filled calibrated vessel with a flexible, elastic, rubber balloon at the base. A valve on the side of the vessel is attached to a pressure gauge to allow application of a controlled pressure to the water to inflate the balloon and measure the volume of the excavated test hole (Rathje et al. 2006). A schematic of the rubber balloon apparatus is presented in Figure 2.1.

Figure 2.1: Rubber balloon apparatus



Source: Weber (2018).

Steel shot

The steel shot replacement device was developed by the U.S. Army Corps of engineers as an alternative to the sand cone test. The density is determined by excavating a hole approximately 4 – 6 inches (100–150 mm) in diameter and weighing the soil. A graduated cylinder is then filled with steel shot to a known volume and the shot is poured into the hole. The volume difference noted in the graduated cylinder is the volume of the test hole (Berney, Meijias-Santiago & Kyzar 2013).

The steel shot replacement device may generally be described as a simplification of the sand cone process, sacrificing accuracy and precision for time. This is because the sand cone test requires constant calibration and access to fresh sand while the steel shot does not, thus allowing tests to be completed in approximately one-third of the time (Berney et al. 2013).

Currently, there is no standardised test method for the operation of the steel shot. The steel shot density kit is presented in Figure 2.2.

Figure 2.2: Steel shot replacement device kit

Source: Berney, Meijias-Santiago and Kyzar (2013).

2.4.2 Penetration Test Methods

Dynamic cone penetrometer

The dynamic cone penetrometer is a relatively simple, portable and low-cost method for the in situ characterisation of pavement layers and subgrades. The test is comprised of a 30 °steel cone attached to a rod that is driven into the ground using a 9 kg drop hammer, from a height of 510 mm (Lee et al. 2017). The results can be reported as either:

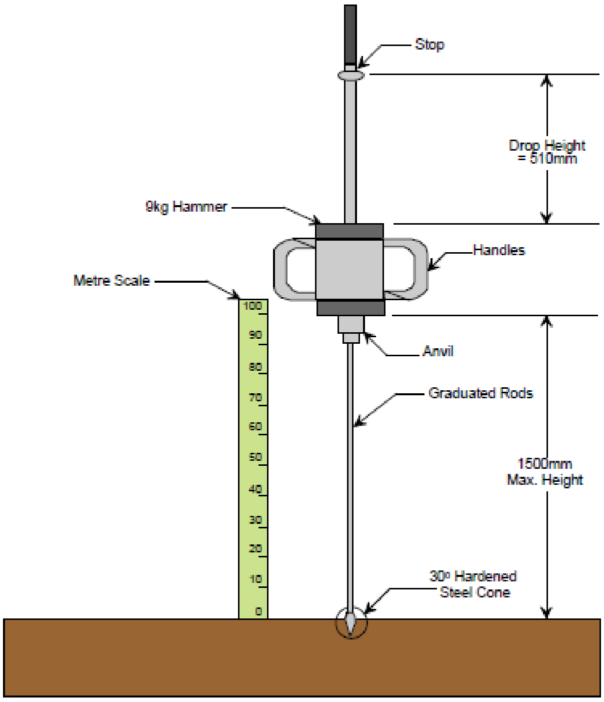
- Penetration resistance (PR) – the number of blows required to produce a rod penetration of a standard length (100 mm or 300 mm).
- DCP ratio (mm/blow) – the length of rod penetration produced per single hammer blow.

The in situ CBR, shear strength or modulus can then be calculated using site-specific correlations or generic correlations such as that shown in Austroads (2017) Figure 5.3 for correlation between the DCP and the CBR for fine-grained soils. Figure 2.3 presents a schematic of the typical components of a DCP.

The DCP is a well-established test method with both national and international specifications, including:

- AS 1289.6.3.2-1997 (R2013), *Methods of testing soils for engineering purposes – soil strength and consolidation tests: determination of the penetration resistance of a soil – 9kg dynamic cone penetrometer test.*
- Queensland Department of Transport and Main Roads (TMR) Test Method Q114B: *Insitu California Bearing Ratio – Dynamic Cone Penetrometer* (TMR 2017).
- ASTM D6951 / D6951M-18, *Standard test method for use of the dynamic cone penetrometer in shallow pavement applications*.

Figure 2.3: Australian DCP test equipment

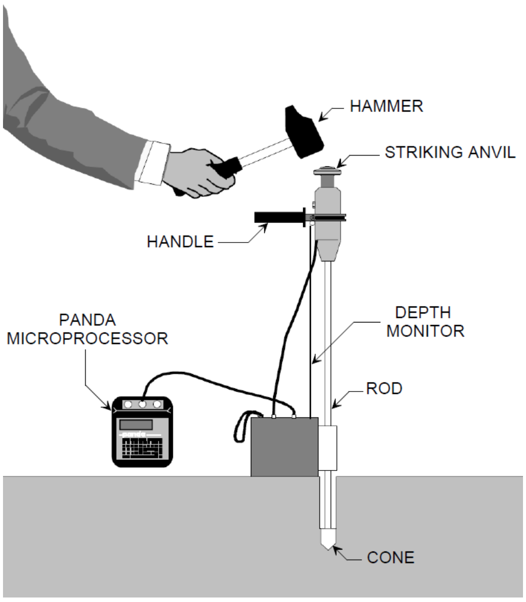


Source: Lee et al. (2017).

PANDA probe

Similar to the DCP, the PANDA probe is a test method in which a cone is manually driven into the soil. This device utilises hammer blows upon an anvil, where the speed of hammer impact and penetration depth is recorded for each blow (Rathje et al. 2006). The mass of the hammer is typically 2 kg, while the impact varies for each blow. Figure 2.4 presents a graphical representation of the key PANDA probe components.

Figure 2.4: PANDA probe penetration test key components



Source: Lee et al. (2017).

Using the applied energy and change of cone depth, the dynamic cone resistance (q_d) can then be calculated using Equation 2.

$$q_d = \left(\frac{1}{A}\right) * \left(\frac{(0.5 * M * v^2)}{1 + \frac{P}{M}}\right) * \left(\frac{1}{x_{90°}}\right) \quad (2)$$

where

q_d	=	dynamic cone resistance
A	=	area of the cone
M	=	weight of hammer
V	=	speed of hammer impact
P	=	weight of struck weight or anvil
$x_{90°}$	=	penetration of one hammer blow (90° cone)

The dynamic cone resistance parameter may then be related to the desired soil material parameters (i.e. shear strength, in situ CBR or modulus) using established correlations (Lee et al. 2017).

Nationally, there is currently no standard test method for the PANDA probe. The only applicable standard is the French Standard, NF P 94-105 *Soils: investigation and testing – inspection of compaction quality – method using a variable energy dynamic penetrometer – principles and method for calibrating the penetrometer – exploitation of results – interpretation* (in French) (AFNOR 2012).

Borehole shear tester

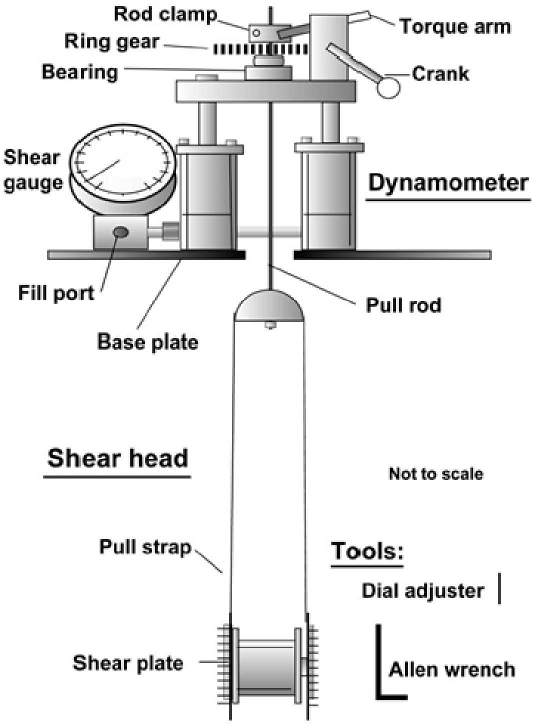
The borehole shear tester (Figure 2.5) can be used to measure the in situ drained shear strength of cohesive fine-grained soils by applying a normal stress and shearing the sides of a small diameter borehole excavated in the compacted layer being assessed. By applying normal and shear forces to the soil, the borehole shear tester can determine the in situ drained friction angle and cohesion of the material for any soil type (Lee et al. 2017).

Testing is conducted by inserting the shear head into a 75 mm diameter borehole to the selected test depth. It is typically carried out in two phases:

- Seating/consolidation phase – a normal stress is applied to the sidewalls of the borehole through the shear plate. The soil is then allowed to consolidate at the applied normal stress for typically between 5–15 minutes.
- Shearing phase – the operator pulls the shear head upward and measures the shear strength of the soil in contact with the plates.

The test is typically repeated four to five times at progressively higher normal stresses to prepare a plot of normal stress against shear stress to determine the Mohr Coulomb failure plane. There are no published Australian or international standard test methods for this test.

Figure 2.5: Borehole shear tester key components



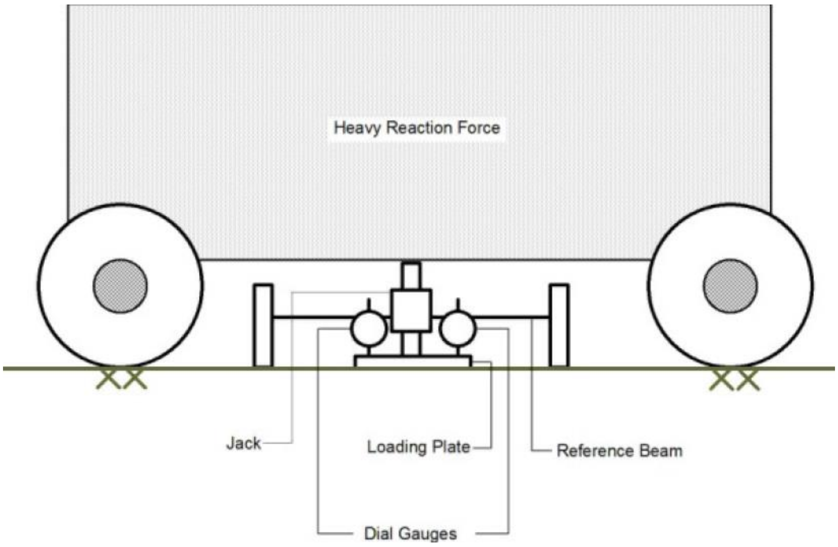
Source: Lee et al. (2017).

2.4.3 Surface-based Impact Devices

Static plate load test

The static plate load test (PLT) is a well-established international test method for determining the in situ static elastic modulus of unbound materials. The test involves apply a compressive load to the test material via the use of a steel plate, hydraulic jack and heavy reaction load, as displayed in Figure 2.6. Independent reference beams and dial gauges are used to measure plate settlements corresponding to the incrementally applied, increasing load (Lee et al. 2017).

Figure 2.6: Static plate load test equipment setup and required reaction load



Source: Lee et al. (2017).

The deflection and stress measurements are then used to plot a stress/deformation curve with the following analysis providing the in situ modulus of the soil. The elastic modulus over the PLT's zone of influence (depth of measurement) can be derived using Equation 3.

$$E_{PLT} = K_S * D * (1 - v^2) \quad (3)$$

where

E_{PLT}	=	elastic modulus over the PLT's zone of influence
K_S	=	subgrade modulus (derived from gradient of stress/deformation curve)
D	=	diameter of rigid plate
v	=	Poisson's ratio

Although there are no Australian standard test methods for the PLT, there are two published ASTM methods viz:

- ASTM D1195 / D1195M-09(2015) – *Standard Test Method for Repetitive Static Plate Load Tests of Soils and Flexible Pavement Components, for Use in Evaluation and Design of Airport and Highway Pavements*.
- ASTM D1196 / D1196M-12(2016) – *Standard Test Method for Nonrepetitive Static Plate Load Tests of Soils and Flexible Pavement Components, for Use in Evaluation and Design of Airport and Highway Pavements*.

Light Falling Weight Deflectometer

The Light Falling Weight Deflectometer (LFWD) utilises a circular loading plate and a weight dropped onto it from a standard height to induce deflection in the pavement material. Although there are a number of LFWDs on the market, the devices share similar mechanics of operation. However, it is important to note that these variations may lead to differing results (Nazzal 2014). The Zorn LFWD is presented in Figure 2.7.

Figure 2.7: Light Falling Weight Deflectometer

Source: Nazzal 2014.

The load plate acts as an accelerometer, recording the change in acceleration with sensors located on top of the plate (Berney et al. 2013). The applied stress and maximum displacement are then related to soil modulus using the Boussinesq elastic half space principle, presented in Equation 4 (Nazzal 2014). However, it is important to note that the resulting modulus from any individual LFWD requires material or site-specific correlation against a reference modulus parameter (i.e. FWD, static plate load test, resilient modulus) for confident implementation (Lee et al. 2017).

$$E_{LFWD} = \frac{(1 - v^2) * \sigma * R * A}{\delta_c} \qquad 4$$

where

E_{LFWD}	=	modulus
v	=	Poisson's ratio (typically 0.3–0.45)
σ	=	applied stress
R	=	loading plate radius
A	=	plate rigidity factor (2 for flexible plate, π/2 for rigid plate)
δ_c	=	central peak deflection

Although there are no national test standards for the LFWD, ASTM has published two applicable standards based on the class of LFWD:

- ASTM E2583-07 (2015) – *Standard Test Method for Measuring Deflections with a Light Weight Deflectometer (LWD).*
- ASTM E2835-11 (2015) – *Standard Test Method for Measuring Deflections using a Portable Impulse Plate Load Test Device.*

Clegg Hammer

The Clegg Hammer is an impact device developed in WA by Dr Baden Clegg to measure the strength/stiffness of soils. The device is comprised of a hammer of variable diameter and mass depending on the application that is fitted with an accelerometer. The accelerometer sends signals to the digital readout upon contact with the soil surface. Once four consecutive drops have been performed at the same location, the largest deceleration measured is termed the Clegg Impact Value (CIV) (Nazzal 2014). The varying sizes and applications for the Clegg Hammer, as well as the proposed equations for converting the CIV to the Clegg Hammer modulus (CHM) are presented in Table 2.4.

Table 2.4: Clegg Hammer applications and conversion equations

Hammer mass (kg)	Hammer diameter (mm)	Recommended applications	CIV to modulus conversion
0.5	50	Soft turf, sand, golf greens	$CHM(MPa) = 0.015(CIV)^2$
2.25	50	Natural or synthetic turf	$CHM(MPa) = 0.044(CIV)^2$
4.5	50	Pre-constructed soils, trench reinstatement, bell holes, foundations	$CHM(MPa) = 0.0.088(CIV)^2$
10	130	Flexible pavement, aggregate road beds, trenches	–
20	130	Reinstatement, bell holes, foundations	$CHM(MPa) = 0.23(CIV)^2$

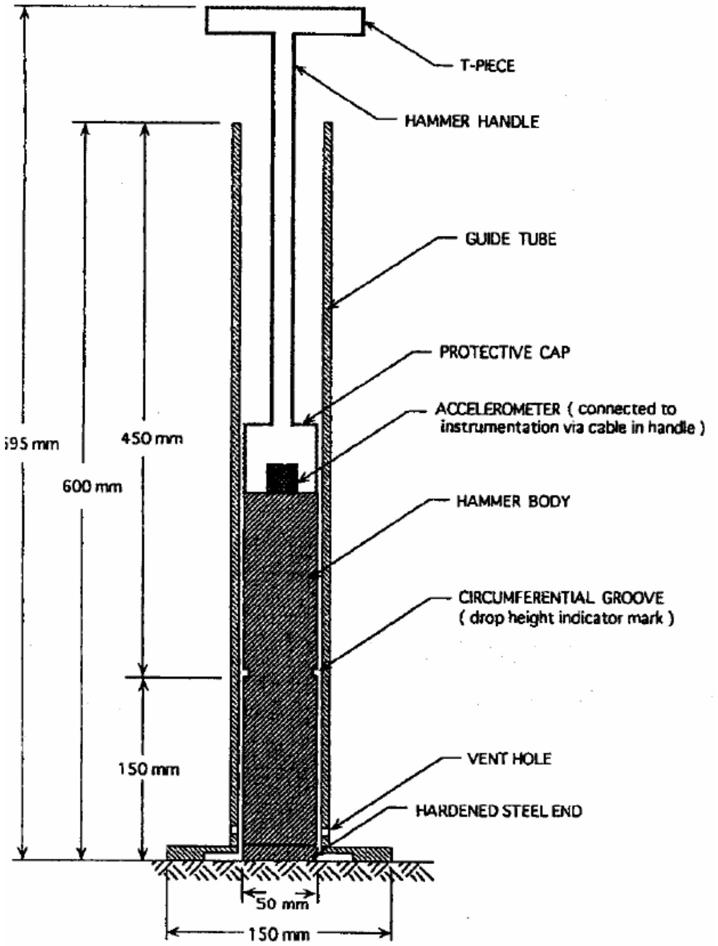
Note: CHM = Clegg Hammer M.

Source: Adapted from Nazzal (2014).

The schematic of the key components of the Clegg Hammer is presented in Figure 2.8. The test method may be conducted in accordance with the following standards:

- AS 1289.6.9.1-2000 (R2013) – *Methods of Testing Soils for Engineering Purposes – Soil Strength and Consolidation Test: Determination of Stiffness of Soil – Clegg Impact Value (CIV).*
- ASTM D5874-16 – *Standard Test Method for Determination of the Impact Value (IV) of a Soil.*

Figure 2.8: Clegg Hammer apparatus key components



Source: Rathje et al. (2006).

It is important to note that MRWA Engineering Road Note 9 (Main Roads Western Australia 2013b) includes a relationship between the CIV and CBR, as presented in Equation 5. However, the correlation must not be used for cohesionless sands without the verification of its appropriateness. The test is to be carried out in accordance with AS 1289.6.9.1.

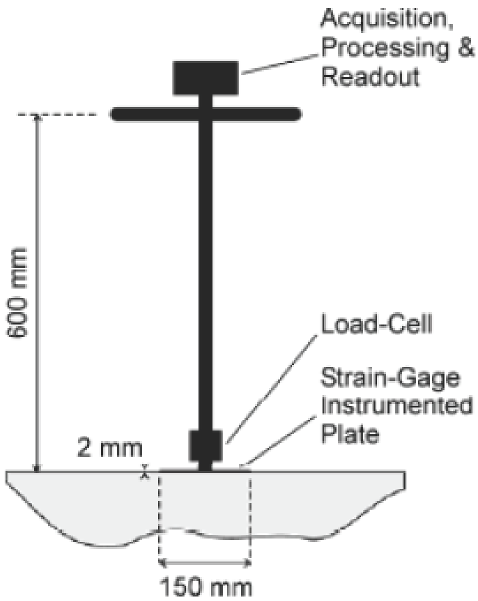
$$CBR = 0.06 * (CIV)^2 + 0.52 * CIV + 1 \quad (5)$$

The Clegg Impact Value is currently specified by MRWA in *Specification 501: Pavements* (Main Roads Western Australia 2018a) for ensuring adequate stiffness in hydrated cement-treated crushed rock basecourse layers prior to sealing. A value of 55 or greater in accordance with AS 1289.6.9.1 is required.

Briaud compaction device

The Briaud compaction device (BCD) works by applying a small repeatable load to a 150 mm diameter flexible thin plate in contact with the compacted material to be tested. The plate is fitted with eight radial and axial strain gauges with a load cell above the plate to measure the force applied by the operator. The application of load causes bending strains in the plate which are measured by the strain gauges. Software within the device then uses field and/or laboratory correlations to calculate the BCD low-strain modulus based on the measured strains (Nazzal 2014). Figure 2.9 presents a schematic of the key BCD components.

Figure 2.9: BCD key components schematic



Currently, there are no published Australian or International standard test methods for the BCD.

GeoGauge

The GeoGauge (Figure 2.10), also referred to as the soil stiffness gauge in the literature, measures the in situ stiffness of compacted soil under 25 programmed steady-state frequencies between 100 and 196 Hz. Testing is carried out by placing the ring-shaped foot on the soil surface, ensuring a minimum of 80% contact between the foot and the soil. If 80% contact cannot be achieved, a thin layer of sand may be used to facilitate contact. The stiffness value output from the gauge is the result of the average stiffness across all 25 frequencies (Nazzal 2014). The measured stiffness can then be converted into modulus using Equation 6 (Lee et al. 2017).

$$E_{SG} = H_{SG}\left[\frac{(1-v^2)}{1.77 * R}\right] \quad 6$$

where

E_{SG} = Young's modulus as measured by the GeoGauge (very low strain)

H_{SG} = GeoGauge stiffness reading

v = Poisson's ratio

R = radius of GeoGauge footing / annulus (57.15 mm)

Figure 2.10: GeoGauge device with external housing

Source: Humboldt (2014).

Soil stiffness may be measured using the GeoGauge in accordance with ASTM D6758-18, *Standard Test Method for Measuring Stiffness and Apparent Modulus of Soil and Soil-Aggregate In-Place by Electro-Mechanical Method.* Notably, no current Australian standard test methods have been published to date.

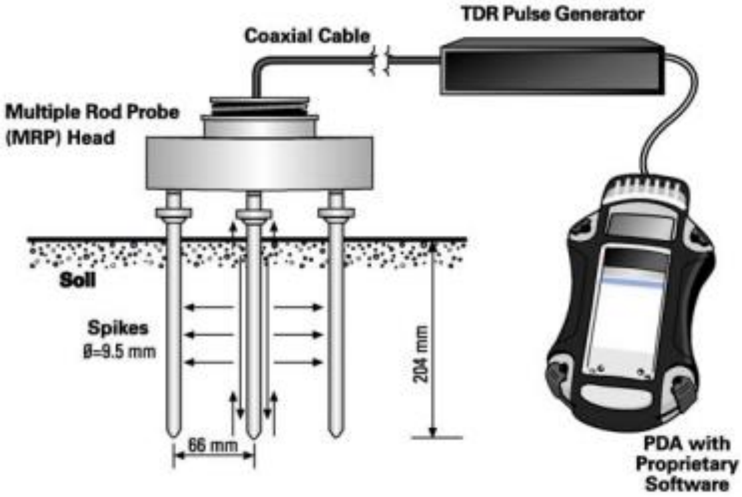
2.4.4 Electrical Moisture-density Devices

Moisture-density indicator

The moisture-density indicator (MDI) measures the wet density and moisture content of material using time domain reflectometry (TDR) that generates an electro-magnetic pulse through four metal spikes driven into the test material. The signal sent by the spikes is then analysed using a personal digital assistant (PDA) or a laptop. The apparent dielectric constant and electrical conductivity of the soil are used to estimate the soil's density and moisture content (Nebraska Transportation Center 2011). A schematic of the key components of the MDI is presented in Figure 2.11.

It is important to note that, in order to determine the dry density of the test soil, moisture density curves using a minimum of four points must be developed using standard (ASTM D698) or modified (ASTM D1557) laboratory compaction techniques.

Figure 2.11: Key components of the MDI



Source: Durham (2005).

This test method is performed in accordance with ASTM D6780 / D6780M-12, *Standard Test Method for Water Content and Density of Soil In situ by Time Domain Reflectometry (TDR).* There are no published Australian standard test methods for this device.

Electrical density gauge

Similar to the MDI, the electrical density gauge (EDG) measures the electrical dielectric properties of the compacted soil. This is achieved by driving four electrodes into the material in a fixed geometric arrangement and transmits radio frequency energy. The EDG then converts these values to density and moisture content using calibration from standard or modified laboratory compaction methods (Berney et al. 2013).

Testing is conducted in accordance with ASTM D7698-11a, *Standard Test Method for In-Place Estimation of Density and Water Content of Soil and Aggregate by Correlation with Complex Impedance Method*. The EDG is displayed in Figure 2.12.

Figure 2.12: EDG components

Source: Sebesta et al. (2013).

Soil density gauge

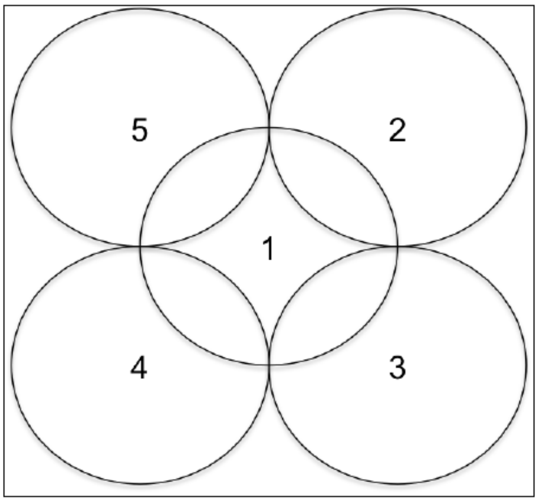
The soil density gauge (SDG) uses electromagnetic impedance spectroscopy to measure the dielectric constant of unbound materials. To calculate the density and moisture content of the soil, the SDG requires soil-specific calibration using traditional test methods such as the sand replacement test for density and convection oven method for moisture content (Rathje et al. 2006). The SDG is shown in Figure 2.13.

Operation of the SDG is in accordance with ASTM D7830 / D7830M-14, *Standard test method for in-place density (unit weight) and water content of soil using an electromagnetic soil density gauge*. This involves placing the device on the soil, testing and moving diagonally in a clover leaf pattern (Figure 2.14).The measurement is done through a non-contacting sensor that consists of a central ring and an outer ring. A radio-frequency-range electromagnetic field is transmitted into the soil using the central ring and received by the outer ring. The response is used to measure the dielectric properties of the soil.

Figure 2.13: SDG

Source: Rathje et al. (2006).

Figure 2.14: Clover leaf pattern for surface placements

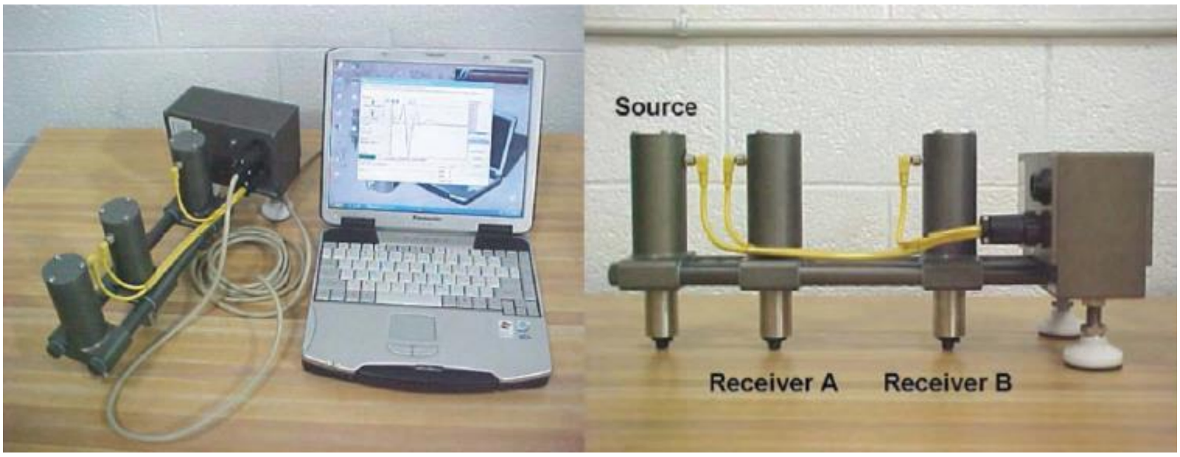


2.4.5 Geophysical Methods

Portable seismic pavement analyser

The portable seismic pavement analyser (PSPA) is a test that estimates the modulus of compacted material using ultrasonic surface waves. The PSPA consists of two geophones and a wave source, which is operated using a laptop, as displayed in Figure 2.15.

Figure 2.15: PSPA components



Source: Nazzal (2014).

High-frequency surface waves are generated by the PSPA that propagate through the material, where the material response is measured by the receivers. The receivers compute the Rayleigh wave velocity at different frequencies, representing the variation of VR at depth (Rathje et al. 2006; Nazzal 2014). Young's modulus can then be determined using Equation 7.

$$E = 2 * \rho * (1.13 - 0.16 * v) * VR^2 \tag{7}$$

where

E	=	Young's modulus (MPa)
ρ	=	total mass density (t/m^3)
v	=	Poisson's ratio
VR	=	Rayleigh wave velocity (m/s)

There are no published Australian or International standard test methods for operation of the PSPA.

2.5 Completed Comparative Studies

A number of research studies have been undertaken to evaluate non-nuclear in situ density test alternatives to replace the NDM. Generally, the studies compare the performance of calibrated alternative methods to the existing NDM over a range of materials, based on a combination of laboratory and field test results, including statistical analyses. Prominent publications that have evaluated the use of alternative QA/QC methods include:

- *Evaluation of non-nuclear methods for compaction control* (Rathje et al. 2006).
- *Non-nuclear compaction gauge comparison study* (Vermont Agency of Transportation 2007).
- *Non-nuclear methods for density measurements* (Nebraska Transportation Center 2011).
- *Evaluation of non-nuclear soil moisture and density devices for field quality control* (Berney & Kyzar 2012).
- *Non-nuclear alternatives to monitoring moisture-density response in soils* (Berney, Meijias-Santiago & Kyzar 2013).
- *Non-nuclear methods for compaction control of unbound materials* (Nazzal 2014).

- *Determination of non-nuclear alternatives to the nuclear density gauge through laboratory and field testing* (Abyad 2016).
- *Review of non-nuclear density gauges as possible replacements for ITD's nuclear density gauges* (Idaho Transportation Department 2015).
- *Alternatives to nuclear density testing* (Mehta & Ali 2016).
- *P60: Best practice in compaction QA for pavement and subgrade materials (year 1 – 2016/2017)* (Lee et al. 2017).
- *Compaction testing of granular materials* (Weber 2018).

The alternative methods, soils evaluated and findings of these studies are summarised in Appendix A and incorporated into Section 2.6.

2.6 Assessment/Ranking of Reviewed Density QA Method

To consolidate the findings from the literature review presented in Appendix A, a criteria list was developed to rank the alternative test devices. The devices were scored relative to the other alternatives according to the criteria and weightings described in Table 2.5. The sand cone/replacement test and the NDM were also ranked for reference.

Table 2.5: Density device ranking criteria

Criterion	Description	Weighting (%)
Relative cost	The cost of the device relative to the other alternative evaluated.	15
Testing time	Relative period of time it takes to complete a test.	15
Ease of use	The simplicity and required level of expertise/training to operate the device (includes safety).	10
Accuracy	The ability of the device to capture the density compared to the reference method (NDM/sand cone); this is generally a measure of possible device testing error.	20
Repeatability/reliability	The variation in measurements taken by a device under the same conditions; a measure of the structural and technical reliability of the device, including operator bias.	20
Standard test method	Whether or not an established standard of measurement exists.	10
Correlations	The number and strength of the relationships between the measured parameter and soil properties.	10

It is important to note that the literature regarding the use of each device is limited for some devices and this may affect the accuracy of the ranking. Assessments based on limited data are noted. Considerations for each criterion are discussed and scored in the following sections.

2.6.1 Relative Cost

The initial and ongoing costs is an important factor when selecting an appropriate density device. Although the initial costs may not necessarily prevent usage, one of the key hindrances with the use of NDMs is the on-going costs associated with ownership, operation, training and the availability of accredited calibration facilities.

Table 2.6 summarises the estimated device costs for each of the alternative density devices reviewed. This includes the approximate initial cost of the device and an estimated yearly maintenance and expenditure cost (e.g. renewing licenses, replacement parts). Furthermore, to estimate the lifecycle cost associated with the use of a single device, the costs have been converted to an approximate 10–year cost.

It is important to note that the maintenance costs for some of the devices could not be determined, and as such will affect the 10–year estimated cost. Devices with a price range (e.g. GeoGauge) were ranked according to the median. Costs that were provided in $USD were converted to $AUD by multiplying the value with the USD/AUD exchange rate at 25 July 2018 (approximately $1.35AUD per $1USD) and rounding to the nearest $500 (Pound Sterling Live (PSL) 2019). Assessments were scored on a scale of 1–3 based upon the relative 10–year estimated cost according to the following:

- (3) – $0–$13 333
- (2) – $13 334–$26 667
- (1) – $26 668–$40 000.

Table 2.6: Cost comparison of alternative density devices

Category	QA method	Approximate initial cost ($AUD)	Maintenance/expenditure cost ($AUD/year)	10–year cost ($AUD)
Traditional methods	NDM	10 000[1]	2 000[1]	30 000
	Sand cone/replacement	750[1]	Not available	750*
Volume replacement method	Steel shot	Not available	Not available	–
Penetration test	DCP	1 300[2]	< 500[1]	6 300
	PANDA probe	27 500[1]	< 500[1]	32 500
	Borehole shear tester	22 000[1]	< 500[1]	27 000
Surface-based impact devices	Static plate load test	30 000[1]	Not available	30 000*
	LFWD	9 000–17 000[1]	2 000[1]	29 000–37 000
	Clegg Hammer	12 000[1]	< 500[1]	17 000
	BCD	Not available	Not available	–
	GeoGauge	6 500–15 000[1]	< 500[1]	11 500–25 000
Electrical moisture-density devices	MDI	8 000[3]	Not available	8 000*
	EDG	12 500[3]	500[4]	17 500
	SDG	13 500[3]	1 000[4]	23 500
Geophysical methods	PSPA	40 500[3]	Not available	40 500*

*Note: Based on initial cost only.

1 Lee et al. (2017).

2 Perth Sand & Dynamic Cone Penetrometers (PSDCP) (2017).

3 Nazzal (2014).

4 Idaho Transportation Department (2015).

2.6.2 Testing Time and Ease of Use

Table 2.7 provides a comparison of the device test duration and the ease of use. The duration per test was based on both the length of time it takes to complete a field test, and the time it takes to complete any associated laboratory testing. Furthermore, as ease of use and site portability is a relatively subjective measure the ranking considered the required training of the operator to achieve accurate results with the device, classified and scored as follows:

- minimal (3) – requires little to no training
- moderate (2) – requires some training
- extensive (1) – requires comprehensive training, which may include licensing.

Similarly, ranking the devices based on the duration of the test was scored using a scale of 1–3. To incorporate both the field and laboratory testing times scoring was based upon the following:

- Field test duration:
  - 1–30 minutes (2)
  - > 31 minutes (1).
- Laboratory testing:
  - Not required (1)
  - Required (0).

Table 2.7: Comparison of testing time, ease of use and required operator training of alternative density devices

Category	QA method	Test duration		Ease of use/operator training
		Field test (min)	Laboratory	
Traditional methods	NDM[1]	1	24 hrs	Extensive
	Sand cone/replacement(1)	30	24 hrs	Minimal
Volume replacement method	Steel shot	10	–	Minimal
Penetration test	DCP(1)	10(1)	–	Minimal(2)
	PANDA probe(1)	10(1)	–	Moderate(3)
	Borehole shear tester(1)	20	–	Minimal
Surface-based impact devices	Static plate load test(1)	60	–	Moderate
	LFWD	5(1)	–	Moderate(2)
	Clegg Hammer	5(1)	–	Minimal(3)
	BCD(2)	1	–	Minimal
	GeoGauge	1(1)	–	Minimal(2)
Electrical moisture-density devices	MDI	15(2)	24 hrs(4)	Moderate(3)
	EDG	1–4(5)	24 hrs(4)	Moderate(3)
	SDG	2(5)	24 hrs(5)	Moderate(2)
Geophysical methods	PSPA	1(6)	–	Extensive(4)

1 Lee et al. (2017).
2 Nazzal (2014).
3 Rathje et al. (2006).
4 Nebraska Transportation Center (2011).
5 Idaho Transportation Department (2015).
6 Anderson (2014).

2.6.3 Accuracy, Repeatability, Reliability and Standard Test Method

The accuracy, repeatability, reliability and the availability of standard test methods for each of the devices is compared in Table 2.8. The device accuracy evaluated the ability of each of the test methods to measure the properties of the soil, accounting for the possibility of any device testing error. For example, the presence of large aggregates may cause penetration-based methods to provide imprecise results. Accuracy rankings and their associated scores are as follows:

- Good (3) – results obtained from the device consistently showed similar values to the reference method.

- Mixed (2) – results obtained from the device showed consistent results in some studies and inconsistent results in others.
- Poor (1) – results obtained from the device were highly variable and inconsistent.

Repeatability and reliability are relatively subjective measures compared to the other device assessment criteria as the literature reviewed assessed repeatability using differing measures. Generally, the repeatability refers to the ability of the device to measure the properties of a soil under the same conditions and return results with minimal variation. Devices with results that may vary with the operator (i.e. reproducibility) are also considered. The repeatability was assessed on a scale of poor, mixed and good. The definitions of the assessment and their ranking scale are as follows:

- Good (3) – results obtained from the device showed constant results and no operator bias across the literature reviewed.
- Mixed (2) – results obtained from the device showed consistent results in some studies and inconsistent results which may include operator bias in others.
- Poor (1) – results obtained from the device were consistently variable and may include operator bias.

Furthermore, consideration was given to devices with a published standard test method and whether it was an Australian or an international method. The ranking of the test methods was based upon the following:

- (3) – Australian test method
- (2) – international test method
- (1) – no test method.

Table 2.8: Comparison of accuracy, repeatability, reliability and standard measurement of alternative density devices

Category	QA method	Accuracy	Repeatability/reliability	Standard test method
Traditional methods	NDM	Good	Good	3
	Sand cone/replacement	–	Mixed	3
Volume replacement method	Steel shot	Poor	Poor	1
Penetration test	DCP	Mixed	Mixed	3
	PANDA probe	Mixed	Mixed	2
	Borehole shear tester	Good	N/A	1
Surface-based impact devices	Static plate load test	Good	Good	2
	LFWD	Good	Mixed	2
	Clegg Hammer	Poor	Good	3
	BCD	Poor	Poor	1
	GeoGauge	Poor	Mixed	2
Electrical moisture-density devices	MDI	Mixed	Mixed	2
	EDG	Mixed	Mixed	2
	SDG	Good	Good	2
Geophysical methods	PSPA	Poor	Good	1

2.6.4 Correlations

Table 2.9 compares the degree of correlation obtained between the in situ test device measurements and those obtained by other traditional in situ tests, as well as the measured parameter/s of the devices. It is important to note that the correlations reported in the reviewed literature are empirical and, as such, can only be used for the conditions similar to those in the study. However, the strength of the derived correlations may indicate the suitability of each of the devices to local conditions and materials.

Generally, the penetration-based devices did not have strong correlations for all soils of interest because the relationship changed with moisture content and plasticity. As the sand cone test method involves excavating a sample and directly measuring the required soil properties the correlations are not applicable. Research on the steel shot, BCD and electrical moisture-density methods and the PSPA is relatively limited and, as such, there are no reported correlations. Similar to previous assessments, scoring was based on the following three-point scale:

- High (3) – reported correlations between the measured parameter and soil properties is strong ($R^2 > 0.80$). Strong correlations may indicate the device's suitability for QA/QC.
- Medium (2) – reported correlations between the measured parameter and soils properties is medium ($0.60 > R^2 < 0.80$) or literature shows varying outcomes. Medium strength correlations may not be suitable for QA but may be applicable for QC.
- Poor (1) – reported correlations between the measured parameter and soil properties is weak ($R^2 < 0.60$) and the device is unsuitable for QA; however, it may be considered for QC.

The correlation strength of each category was scored on the three-point scale and the final score divided by three. For ranking purposes, the sand cone test was allocated a score of three and the devices without reported correlations were allocated a score one. A summary of the assessment is presented in Table 2.10.

Table 2.9: Comparison of strength of correlation of alternative density devices

Category	QA method	Measured parameter	Strength of correlations		
			Cohesive	Sand	Gravel
Traditional methods	NDM	Dry density, moisture content	High	High	High
	Sand cone/replacement	Dry density	N/A	N/A	N/A
Volume replacement method	Steel shot	Dry density	–	–	–
Penetration test	DCP	DCP penetration index	Poor	High	Medium
	PANDA probe	Cone tip resistance	Medium	High	High
	Borehole shear tester	In situ Mohr-Coulomb strength parameters	High	Medium	Poor
Surface-based impact devices	Static plate load test	Modulus	High	High	High
	LFWD	Modulus	Medium	High	High
	Clegg Hammer	Clegg Impact Value	Poor	Medium	Medium
	BCD	Modulus	–	–	–
	GeoGauge	Modulus	Poor	Medium	Medium
Electrical moisture-density devices	MDI	Dry density, moisture content (laboratory calibration using standard or modified Proctor test)	–	–	–
	EDG	Dry density, moisture content (field calibration using direct measurement of dry density and moisture content)	–	–	–
	SDG	Dry density, moisture content (field calibration using direct measurement of dry density and moisture content)	–	–	–
Geophysical methods	PSPA	Modulus	–	–	–

Source: adapted from Lee et al. (2017).

2.6.5 Ranking

The results of the assessment and scoring for each criterion and for each device are presented in Table 2.10, where the weighted totals with the highest scores are the most desirable options. The overall rankings for each of the alternative compaction QA devices were:

1. Sand replacement test (2.50) – traditional method
2. DCP (2.50) – penetration test
3. Nuclear Density Meter (2.35) – traditional method
4. Static plate load tester (2.35) – surface-based impact test
5. Clegg Hammer (2.32) – surface-based impact test
6. SDG (2.30) – electrical moisture-density device
7. LFWD (2.27) – surface-based impact devices
8. PANDA probe (2.07) – penetration test
9. MDI (2.05) – electrical moisture-density device
10. GeoGauge (2.02) – surface-based impact device
11. Borehole shear tester (2.00) – penetration test

12. EDG (1.90) – electrical moisture-density device
13. PSPA (1.70) – geophysical method
14. BCD (1.50) – surface-based impact device
15. Steel shot (1.50) – volume replacement test.

The results of the assessment indicate that there are several devices that have the potential to replace the NDM as a QA compaction tool. However, consideration must be given to each of the identified issues and disadvantages of the alternative devices.

It is important to note that the rankings are based on a majority of studies conducted in the USA and would require consideration within the Australian environment. Furthermore, findings reported in the literature regarding the applicability of the alternative devices for QA were often contradictory and additional field evaluations may be required before implementation could be considered.

Table 2.10: Summary of assessment of QA density test methods

Category	QA method	Cost (15%)	Test time (15%)	Ease of use (10%)	Accuracy (20%)	Repeatability/reliability (20%)	Standard measurement (10%)	Correlation (10%)	Weighted total
Traditional methods	NDM	1	2	1	3	3	3	3	2.35
	Sand cone/replacement	3	1	3	3	2	3	3	2.50
Volume replacement method	Steel shot	1	3	3	1	1	1	1	1.50
Penetration test	DCP	3	3	3	2	2	3	2	2.50
	PANDA probe	1	3	2	2	2	2	2.67	2.07
	Borehole shear tester	1	3	3	3	1	1	2	2.00
Surface-based impact devices	Static plate load test	1	2	2	3	3	2	3	2.35
	LFWD	1	3	2	3	2	2	2.67	2.27
	Clegg Hammer	2	3	3	1	3	3	1.67	2.32
	BCD	1	3	3	1	1	1	1	1.50
	GeoGauge	2	3	3	1	2	2	1.67	2.02
Electrical moisture-density devices	MDI	3	2	2	2	2	2	1	2.05
	EDG	2	2	2	2	2	2	1	1.90
	SDG	2	2	2	3	3	2	1	2.30
Geophysical methods	PSPA	1	3	1	1	3	1	1	1.70

2.7 Findings and Recommendations

Based on the review of the alternative QA/QC field density methods for sand materials typical of subgrade and embankment fill, it is evident that there are a vast range of existing options. However, the most common practice, both nationally and internationally, for field density QA/QC of subgrades and embankments are the sand replacement (sand cone) and NDM methods.

Penetration tests, surface-based impact methods and electrical-moisture density devices appear to be the most frequently researched non-nuclear methods in the USA. However, none of these alternative methods have been officially implemented or included in road authority specifications.

It is important to note that comparisons between MRWA practice and the literature reviewed for this project (primarily US-based) requires careful consideration due to fundamental differences in pavement design, local conditions, material availabilities and QA/QC requirements.

General findings resulting from the review include:

- The literature indicates that several non-nuclear compaction devices have the potential to replace the NDM as a compaction QA/QC tool. However, the findings of several studies were contradictory.
- Generally, the applicability of the alternative devices is limited by the strength of the correlations relating the alternative device output to density.
- Based on a comparative assessment of cost, test time, ease of use, accuracy, repeatability, reliability, availability of standard test methods and the strength of correlations, the equipment with the highest weighted ratings was the dynamic cone penetrometer (DCP), static plate load tester, Clegg Hammer, SDG and the LFWD.
- The DCP was the highest scoring alternative device that was evaluated, indicating that it has the potential to replace the NDM. However, the device has notable issues associated with its use for granular and plastic material which may affect adoption. In addition, the testing time is slow and it can be physically demanding after a period of time in operation.
- Although the static plate load tester is an accepted method for determining in situ modulus, the primary limitation is the test cost and duration.
- The applicability of the Clegg Hammer for field density QA/QC may be restricted by the strength of the correlations with other devices.
- The main advantage of the SDG is that, similar to the NDM, the device can measure both the field density and moisture content. However, the device requires extensive operator training and must be calibrated using a traditional NDM device.
- The LFWD shows significant potential for use as a field density QA/QC tool in Australia. Notably, it has already been used successfully on trials conducted in Queensland by TMR. The primary reason for its reduced score was due to the relatively large investment required as it scored well in other categories. If the cost of the device were not an issue, the LFWD would have been the highest ranked alternative device.
- The least desirable alternatives reviewed were the steel shot, which was not developed as a QA/QC tool, and the Briaud compaction device, due to limited available information.

Due to the disadvantages of using the sand replacement method and the NDM for QA/QC testing, it is recommended that the use of non-nuclear, alternative density test methods is further investigated by MRWA.

Recommendations for future study include:

- Conduct a series of field trials on fine-grained subgrades involving the use of both the SDG and the LFWD to measure in situ density and compare the results obtained with the results of testing using currently available equipment, including the NDM and sand replacement test. Such a trial would require MRWA to invest in the purchase of the SDG and a LFWD as well as the associated training.
- Source any available test data from local or national contractors that use any of the alternative devices as a QC tool.
- Based on these investigations, develop a test method/methods and a standard calibration procedure/procedures for the SDG and/or the LFWD.
- Update MRWA documentation to allow the use of non-nuclear density testing devices (SDG and/or LFWD) as an alternative to the sand replacement test or the NDM.

3 ALTERNATIVE, NON-DESTRUCTIVE METHODS TO ASSESS DRY-BACK OF CONSTRUCTED SUBGRADES

3.1 Current Dry-back Assessment

Dry-back is a critical process in the construction of granular pavement layers as poor or incomplete dry-back may increase the risk of the pavement prematurely deforming under traffic loads due to the retention of excess moisture (Austroads 2014).

The current QA/QC procedures for sands typically ensure dry-back using the laboratory convection oven or the NDM. However, the standard oven moisture test is time-consuming and destructive, requiring material excavation from the subgrade layer. Furthermore, using the NDM requires recurring calibration against the laboratory oven technique and compliance with the strict safety and operational restrictions associated with using nuclear material.

There are several alternative non-destructive, non-nuclear methods for measuring the in situ moisture content of unbound materials during construction that have been investigated. The current assessment procedures, as well as the alternative methods, are discussed in the following sections.

Table 3.1: Summary of current methods for moisture determination

QA method	Description	Test method
Convection oven/oven dry	An in situ sample is taken from the soil of interest, weighed and dried using a laboratory oven. The mass loss is assumed to be entirely water, and the moisture content of the soil can be calculated.	AS 1289.2.1.1 WA 110.1 ASTM D2216
Microwave oven	Similar to the convection oven method, an in situ soil sample is weighed and dried using a microwave oven and the moisture content of the soil is calculated using the wet and dry mass of the soil.	AS 1289.2.1.4 WA 110.2 ASTM 4643
NDM	The NDM emits radiation from an Americium isotope into the soil and a detector on the gauge determines the amount of radiation reflected back, which is then related to the moisture content of the soil.	AS 1289.5.8.1 WA 324.2 Qld N02

3.1.1 MRWA Dry-back

Currently, the process of sampling is a destructive process that requires material excavation from the completed pavement layers. *Specification 201* (Main Roads Western Australia 2018b) states that for subgrade and embankment works there must be at least six tests per lot. Following sampling, the moisture content of the material is determined in accordance with the convection oven method, WA 110.1. Where it is not practicable to use WA 110.1, then MRWA allow moisture content to be determined using the NDM (WA 324.2) or the microwave oven method (WA 110.2). Notably, before moisture content may be determined with either the NDM or the microwave oven method, correlation must be established with the convection oven method.

The dry-back characteristic moisture content (DM_c) of a lot is subsequently calculated using Equation 8:

$$DM_c = m + ks \quad (8)$$

where

DM_c	=	dry-back characteristic moisture content (%)
m	=	average of the sample moisture contents on the lot being assessed, taken from the pavement layer and determined in accordance with WA 110.1
k	=	multiplier, varies with standard of works component (i.e. freeways, highways and MRWA, or shared paths)
s	=	standard deviation of the results of the in situ moisture content tests on the lot being assessment

In accordance with *Specification 501 Pavements* (Main Roads Western Australia 2018a) pavement construction shall not commence until the layer 150 mm below the subgrade has dried back until the DM_c is equal to or less than the proportion of the OMC determined using WA 133.1 or WA 133.2, as applicable. The MRWA requirements for the dry-back of pavement layers is summarised in Table 3.2. Notably, MRWA do not currently specify the required dry-back for subgrade or embankment materials in addition to Perth sands.

Table 3.2: MRWA requirements for dry-back of pavement layers

Pavement layer	Maximum DM_c as a proportion of OMC (%)
Layer 150 mm below subgrade surface (except for Perth sand)	85
Drainage layer	Not required
Sub-base	85
Basecourse (final surfacing – sprayed seal)	85
Basecourse (final surfacing – asphalt)	70
Crushed rock base (all surfacing types)	60
Hydrated cement treated crushed rock base (all surfacing types)	70

Source: MRWA (2018b).

Convection oven method

The convection oven method, in accordance with WA 110.1, describes the procedure for determining the moisture content, as a percentage of dry mass, by oven-drying soils and granular pavement materials. To determine the moisture content, soil samples are taken from the prepared subgrade or embankment foundation by excavation in accordance with WA 100.1. The mass of the sample varies based upon the nominal maximum particle size of the material, as summarised in Table 3.3.

Table 3.3: Minimum mass per sample increase for moisture content determinations

Nominal maximum size (mm)	Mass (kg)
80–41	5
40–20	3
< 20	1

Source: MRWA (2011c).

The sample is then placed in an oven at a temperature of 105–110 °C to dry. The length of drying time varies with the soil type, quantity and wetness. Soil mass is checked at one hour intervals until constant mass is achieved. Moisture content may then be calculated using Equation 9.

$$w = \frac{m_2 - m_3}{m_3 - m_1} * 100 \qquad (9)$$

where

w	=	Moisture content as a percentage of dry soil mass
m_1	=	Container mass (g)
m_2	=	Container mass plus wet soil (g)
m_3	=	Container mass plus dry soil (g)

Microwave oven method

The microwave oven method, WA 110.2 (Main Roads Western Australia 2011b) follows the same principle as the convection oven method. However, the microwave oven method may not be used if it is practicable to use the convection oven method. The microwave oven method must also have an established correlation with the convection oven method for the materials that are to be tested (Main Roads Western Australia 2011b).

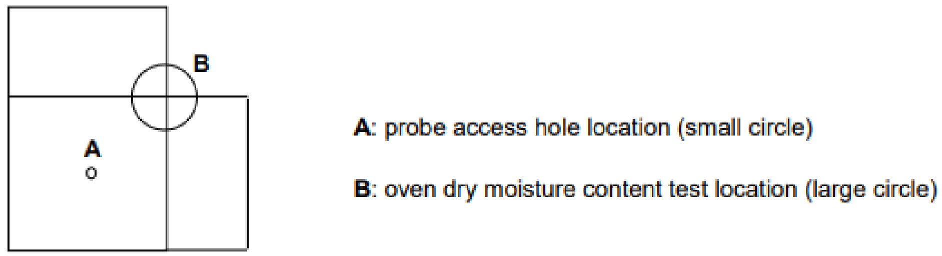
Determination of moisture content is conducted by placing a container of the wet soil sample in the microwave oven to dry. Drying times vary depending on the soil type and mass. Soil mass is checked at periods of one minute for clays, and two minutes for all other materials until constant mass is achieved. The moisture content is then calculated using Equation 9.

Nuclear density method

Specification 201 states that if it is not practicable to use the convection oven method for determining the moisture content of soil then the NDM, in accordance with WA 324.2, may be used if there is an established correlation with the convection oven method. However, WA 342.2 does not describe a procedure for the determination of in situ moisture content of soils and granular pavement materials using the NDM. Personal correspondence with Main Road indicates that, in WA, the NDM is rarely used to determine the moisture content of soil due to backscatter measurement mode depth limitations.

As such, determining the correlation between the NDM and the convection oven method may be carried out in accordance with TMR *Test method N02: Material bias – soil moisture content* (TMR 2018c). In this method at least six test sites within a lot are selected and tests using both the NDM and the convection oven method are conducted as shown in Figure 3.1. The tests are then correlated using the standard blocks moisture content values determined for all test sites.

Figure 3.1: NDM moisture testing locations



Source: TMR (2018c).

3.2 Alternative, Non-Destructive Methods to Assess Dry-back

3.2.1 Introduction

The alternative methods for assessing dry-back that have been evaluated in literature can typically be categorised into the following groups:

- electrical moisture-density devices:
  - devices that attempt to relate the electrical properties of the soil to the dry unit weight and moisture content of the soil.
- gravimetric (direct heat) methods:
  - techniques that directly determine the moisture content of soil by determining the mass of a collected soil sample, apply heat using blow torches, hot plates or similar to evaporate moisture and determining the mass of the dried sample.
- chemical methods:
  - devices that indirectly measure the moisture content of soil by determining the amount of gas produced by a reactant material and the free moisture in the soil.

Table 3.4 presents a summary of the non-destructive methods of assessing soil dry-back evaluated as part of this review, and the associated test method where available. It is important to note that the literature reviewed evaluated a significant number of destructive tests, primarily gravimetric methods, which were not included in this review.

Table 3.4: Summary of the non-destructive, alternative methods for assessing dry-back

Category	QA method	Description	Test method
Electrical moisture-density devices	MDI	The MDI uses a time domain reflectometry to determine the wet density and moisture content of a material. This is achieved by generating an electro-magnetic pulse through four metal spikes driven into the test material. The voltage signal returned is analysed by software to estimate soil wet density and moisture content.	▪ ASTM D6780 / D6780M-12
	EDG	The EDG uses high radio frequency energy transmitted into the material to measure the density and moisture content through tapered darts driven into the soil in a specific geometry.	▪ ASTM D7698
	SDG	By using an advanced electrical impedance spectroscopy, the SDG allows for non-contact measurements of soil density and moisture content. The compaction level is measured by the changes in electrical impedance of the material matrix. A known moisture and density reading on the soil of interest is required to calibrate the density and moisture content.	▪ ASTM D7830 / D7830M-14
	Percometer	Estimates the moisture content by measuring the dielectric permittivity and conductivity using a probe.	▪ N/A
	Trident moisture meter	Using a five-pronged sensor, the moisture content of sand, gravel, crushed stone and other fine and coarse aggregates is determined using dielectric permittivity.	▪ N/A
Chemical	'Speedy' moisture tester	Measures the moisture content of the soil by determining the amount of acetylene gas produced by a reactant material (calcium carbide) and the free moisture of the soil. The method assumes all free water in the soil reacts with the calcium carbide.	▪ ASTM D4944 ▪ AASHTO T217

3.2.2 Electrical Moisture-density Devices

Moisture Density Indicator, Electrical Density Gauge and Soil Density Gauge

A summary of the equipment, operation and standard test methods for the MDI, EDG and SDG is provided in Section 2.4.4.

Percometer

The Percometer is comprised of a 600 mm diameter probe that is designed for insertion into soft materials at a minimum depth of 100 mm for accurate measurements. When the probe is pressed against the test material, the device emits a small electrical current and the dielectric permittivity and conductivity values are calculated as the current moves through the test material between electrodes on the probe (Nazzal 2014).

Figure 3.2: Percometer

Source: Humboldt (n.d.).

No Australian or international standard test methods exist for the use of the Percometer.

Trident moisture meter

The Trident moisture meter utilises a five-pronged sensor to measure the complex dielectric constant of a test material. An integrated microprocessor converts the dielectric constant to a moisture content value as a percentage of the dry weight. Therefore, to ensure accuracy of the reading, material-specific calibration is required and it is recommended that an average of five to ten readings is taken. It is important to note that device cannot be used for material with a nominal particle size greater than 25 mm (Nazzal 2014).

Figure 3.3: Trident moisture meter

Source: James Instruments (2019).

The use of the Trident moisture meter is not covered by any Australian or international standard test method.

3.2.3 Chemical-based Devices

Speedy moisture tester

The 'Speedy' moisture tester™ measures the moisture content of soil by determining the amount of gas produced by a reactant material (calcium carbide) and the free moisture of the soil. The device consists of a plastic case containing a low-pressure vessel fitted with a pressure gauge, an electronic scale, steel balls, calcium carbide and a brush, as shown in Figure 3.4.

Figure 3.4: Speedy moisture tester

Source: Berney et al. (2011).

The test involves taking a 20 g sample of soil and placing it into the moisture container with a specified amount of calcium carbide powder, placing two steel balls into the device and sealing.

The operator then shakes the device so that the steel balls break up any lumps in the sample, ensuring all of the moisture reacts with the calcium carbide. This produces carbon dioxide from the water-chemical reaction and the pressure change is recorded by the device and related to gravimetric moisture content. Notably, this method assumes all free water in the test material reacts with the calcium carbide (Berney et al. 2011).

The Speedy moisture tester shall be used in accordance with the following standards:

- ASTM D4944-18 – *Standard test method for field determination of water (moisture) content of soil by the calcium carbide gas pressure tester*.
- AASHTO T217-2014 – *Standard method of test for determination of moisture in soils by means of a calcium carbide gas pressure moisture tester*.

3.3 Comparative Studies

There are a number of alternative, non-destructive tests for determining the in situ moisture content of soil that have been proposed and evaluated in the literature. However, the number of studies that have been conducted varies with each device. Similarly to the NDM density alternatives, the majority of the studies have been conducted in the USA, involving comparing the performance of calibrated alternative methods to the laboratory oven method and the NDM using laboratory and field investigations. The key documents reviewed provide comprehensive summaries of the alternative technologies, incorporating publications from around the world. These documents include:

- *Evaluation of non-nuclear methods for compaction control* (Rathje et al. 2006).
- *Non-nuclear compaction gauge comparison study* (Vermont Agency of Transportation 2007).
- *Device comparison for determining field soil moisture content* (Berney et al. 2011).
- *Performance-based measurement of optimum moisture for soil compaction* (Hanson & Nieber 2013).
- *Initial review of rapid moisture measurement for roadway base and subgrade* (Sebesta et al. 2013).
- *Non-Nuclear Methods for Compaction Control of Unbound Materials* (Nazzal 2014).

Appendix B presents the non-destructive alternative test methods, an assessment of their use as a QA tool and any noted issues/limitations that may prevent usage. Although the NDM is generally considered a well-established test method, it is included as a point of comparison.

3.4 Assessment/Ranking of Reviewed Moisture Content QA Methods

The literature review findings presented in Appendix B were sufficient to develop a preliminary ranking of each device. The non-destructive moisture determination devices were scored relative to the identified test methods according to the parameters outlined in Table 3.5. The convection oven, microwave oven and NDM methods were included for reference.

It is important to note that the literature regarding the use of each device is limited for some devices and this may affect the accuracy of the ranking. Assessments based on limited data are noted. The following sections discuss the criteria and how each parameter was scored for ranking.

Table 3.5: Non-destructive moisture device ranking criteria

Criteria	Description	Weighting (%)
Relative cost	The cost of the device relative to the other alternative evaluated.	15
Test time	Relative period of time it takes to complete a test.	15
Ease of use	The simplicity and required level of expertise/training to operate the device (includes safety).	10
Accuracy	The ability of the device to capture the moisture content compared to the reference method (convection oven/NDM). This is generally a measure of possible device testing error.	20
Repeatability/reliability	The variation in measurements taken by a device under the same conditions. A measure of the structural and technical reliability of the device.	20
Standard test method	Whether or not an established standard of measurement exists.	10
Suitability for sand	The applicability of the test method for compacted sand.	10

3.4.1 Relative Cost

The approximate cost of purchasing and maintaining the devices, as well as the estimated 10–year cost is presented in Table 3.6. However, the maintenance costs could not be determined for a number of devices which may affect the accuracy of the assessment. As outlined in Section 2.6.1, costs that were provided in $USD were converted to $AUD by multiplying the value with the USD/AUD exchange rate at 25 July 2018 (approximately $1.35AUD per $1USD) and rounding to the nearest $500 (Pound Sterling Live (PSL) 2019).

Table 3.6: Cost comparison of non-destructive dry-back methods

Category	QA method	Approximate initial cost ($AUD)	Maintenance/expenditure costs ($AUD/year)	10–year cost ($AUD)
Traditional methods	Convection oven	2 000(1)	Not available	2 000*
	Microwave oven	1 000(2)	Not available	1 000*
	NDM	10 000(3)	2 000(3)	30 000
Electrical moisture-density devices	MDI	8 000(4)	Not available	8 000*
	EDG	12 500(4)	500(5)	17 500
	SDG	13 500(4)	1 000(5)	23 500
	DOT600 roadbed water content meter	4 000(6)	Not available	4 000*
	Percometer	10 500(4)	Not available	10 500*
	Trident moisture meter	2 500(4)	Not available	2 500*
Chemical	Speedy moisture tester	3 000(6)	Not available	2 600*

* Note: Based on initial cost only.

Source:
1 Ladd Research Industries (LRI) (2018a).
2 Ladd Research Industries (LRI) (2018b).
3 Lee et al. (2017).
4 Nazzal (2014).
5 Idaho Transportation Department (2015).
6 Sebesta et al. (2013).

Assessments were scored on a scale of 1–3 based upon the relative 10–year estimated cost according to the following:

- (3) – $0–$10 000 10–year cost
- (2) – $10 001–$20 000 10–year cost
- (1) – $20 001–$30 000 10–year cost.

3.4.2 Test Time and Ease of Use

The duration of the in situ test, the laboratory test (if required) and the ease of use of the device are summarised in Table 3.7. The ease of use was scored according to the following:

- minimal (3) – requires little to no training
- moderate (2) – requires some training
- extensive (1) – requires comprehensive training, which may include licensing.

The scoring of the non-destructive dry-back test methods was in accordance with the following:

- Field test duration:
  - 1–10 minutes (2)
  - > 11 minutes (1).
- Laboratory testing:
  - Not required (1)
  - Required (0).

Table 3.7: Test time, ease of use and required operator training comparison of non-destructive methods

Category	QA method	Test duration		Ease of use/operator training
		Field test (min)	Laboratory	
Traditional methods	Convection oven	–	12 hrs[1]	Minimal
	Microwave oven	–	0.5 hrs[1]	Minimal
	NDM[2]	1	24 hrs	Extensive
Electrical moisture-density devices	MDI	15[3]	24 hrs[4]	Moderate[5]
	EDG	1–4[6]	24 hrs[4]	Moderate[5]
	SDG	2[6]	24 hrs[6]	Moderate[3]
	Percometer	–	–	Minimal[3]
	Trident moisture meter	1	–	Minimal[3]
Chemical	Speedy moisture tester	5[1]	–	Extensive[5]

1 Sebesta et al. (2013).
2 Lee et al. (2017).
3 Nazzal (2014).
4 Nebraska Transportation Center (2011).
5 Rathje et al. (2006).
6 Idaho Transportation Department (2015).

3.4.3 Accuracy, Repeatability, Reliability and Standard Test Method

Table 3.8 summarises the accuracy, repeatability, reliability and the availability of standard test methods for each of the methods reviewed. Accuracy was scored as follows:

- Good (3) – results obtained from the test method consistently showed similar values to the reference method.
- Mixed (2) – results obtained from the test method showed consistent results in some studies and inconsistent results in others.
- Poor (1) – results obtained from the test method were highly variable and inconsistent.

The repeatability/reliability of the test method was assessed on three-point scale as follows:

- Good (3) – results obtained from the device showed constant results and no operator bias across the literature reviewed.
- Mixed (2) – results obtained from the device showed consistent results in some studies and inconsistent results which may include operator bias in others.
- Poor (1) – results obtained from the device were consistently variable and may include operator bias.

Standard test method ranking was scored according to the following system:

- (3) – Australian test methods
- (2) – international test methods
- (1) – no test methods.

Table 3.8: Non-destructive method accuracy, repeatability, reliability and standard test methods

Category	QA method	Accuracy	Repeatability/reliability	Standard test method
Traditional methods	Convection oven	Good	Good	3
	Microwave oven	Good	Good	3
	NDM	Good	Good	3
Electrical moisture-density devices	MDI	Mixed	Mixed	2
	EDG	Good	Good	2
	SDG	Good	Good	2
	Percometer	Poor*	Poor*	1
	Trident moisture meter	Good*	Poor*	1
Chemical	Speedy moisture tester	Poor	Good	2

* Note: Based on limited information.

3.4.4 Suitability for Sand

Pavement subgrades in MRWA's controlled assets are typically sands and, as such, the suitability of the non-destructive dry-back methods for use in sand will influence its applicability to WA conditions. Table 3.9 summarises the suitability of each reviewed method for sand based upon the outcomes of the literature reviewed. For ranking purposes, the methods were scored on a two-point scale as follows:

- Yes (3) – suitable for sand.
- No (0) – unsuitable for sand.

Table 3.9: Non-destructive method suitability for sand

Category	QA method	Suitability for sand
Traditional methods	Convection oven	Yes
	Microwave oven	Yes
	NDM	Yes
Electrical moisture-density devices	MDI	Yes
	EDG	Yes
	SDG	Yes
	Percometer	Yes*
	Trident moisture meter	Yes*
Chemical	Speedy moisture tester	No

* Note: Based on limited information.

3.4.5 Ranking

Table 3.10 summarises the scores for each test method based on the reviewed literature outcomes. Methods with the same overall weighted score were ranked according to which method had the greater number of “3’s”. The ranking of the non-destructive moisture determination methods was:

1. Convection Oven (2.85) – traditional method
2. Microwave Oven (2.85) – traditional method
3. EDG (2.50) – electrical moisture-density device
4. SDG (2.50) – electrical moisture-density device
5. Trident moisture meter (2.40) – electrical moisture-density device
6. NDM (2.35) – traditional method
7. MDI (2.10) – electrical moisture-density device
8. Percometer (2.00) – electrical moisture-density device
9. Speedy moisture tester (2.00) – chemical device.

The scores indicate that some of the alternative, non-destructive methods of moisture determination may be suitable for implementation. However, it is important to note that the evaluation of some of the methods was based on relatively limited literature and as such, may require further evaluation.

3.5 Findings and Recommendations

The purpose of the literature review of alternative, non-destructive methods was to determine whether the extent of dry-back of subgrade materials could be assessed without excavating samples from the compacted pavement layers. The literature reviewed was primarily based on USA work and, as such, the findings need to be carefully considered due to differences in pavement design, local conditions, material availabilities and QA requirements.

Findings from the literature review include:

- MRWA does not currently allow the NDM to be used for moisture content determinations due to backscatter measurement mode depth limitations.

- Typical national and international practice for determining the moisture content of in situ soils includes the use of the convection oven (oven-dry method), microwave oven and the NDM.
- Evaluation of the alternative test methods indicates that there are a number of potential non-destructive options for assessing subgrade and embankment dry-back.
- Literature regarding the non-destructive evaluation of soil moisture content was relatively limited and was primarily based in the USA.
- The most frequently researched alternative, non-destructive test methods reviewed were electrical-moisture density devices and the chemically-based 'Speedy' moisture tester.
- Based on the comparative assessment of cost, test time, ease of use, accuracy, repeatability, reliability, availability of standard test methods and suitability for sand the most promising device is the electrical density gauge.
- The least desirable alternatives were the Percometer and the 'Speedy' moisture tester.
- Although the NDM is a well-established test method with a proven track record of assessment, its scores were reduced due its comparatively high cost and the extensive training required for use.

The literature review findings indicate that non-destructive test methods for the determination of in situ soil moisture content for the purpose of monitoring dry-back may be applicable for use in WA. However, practical evaluations on a variety of local materials and methods need to take place. Recommendations for future study include:

- Source any available test data from local or national contractors regarding the use of the NDM for moisture content determination and dry-back control. This would allow the evaluation of the use of the NDM as a non-destructive alternative to the convection oven method for determining the dry-back of embankment and subgrade materials in WA.
- Conduct field evaluations using selected non-destructive, non-nuclear devices and determine the in situ moisture content of materials typically used for subgrades and embankments in WA and compare the results with current MRWA practice for achieving dry-back. This may include the electrical density gauge, the soil density gauge and the Trident moisture meter although this may vary with equipment availability. This may be conducted at the same time as the proposed density testing outlined in Section 2.
- Based on further investigation of an alternative in line with the above steps, develop a test method and standard calibration procedure.
- Update MRWA documentation to allow the use of non-destructive moisture determination testing devices as an alternative to the convection oven method.

Table 3.10: Scoring of the non-destructive moisture determination methods based on literature review

Category	QA method	Cost (15%)	Test time (15%)	Ease of use (10%)	Accuracy (20%)	Repeatability/reliability (20%)	Standard measurement (10%)	Suitability for sand (10%)	Weighted total
Traditional methods	Convection oven	3	1	3	3	3	3	3	2.85
	Microwave oven	3	1	3	3	3	3	3	2.85
	NDM	1	2	1	3	3	3	3	2.35
Electrical moisture-density devices	MDI	3	1	2	2	2	2	3	2.10
	EDG	2	2	2	3	3	2	3	2.50
	SDG	2	2	2	3	3	2	3	2.50
	Percometer	3	3	3	1	1	1	3	2.00
	Trident moisture meter	3	3	3	3	1	1	3	2.40
Chemical	Speedy moisture tester	3	3	1	1	3	2	0	2.00

4 METHOD SPECIFICATION FRAMEWORK FOR PERTH SAND PENETROMETER AND DENSITY QC

4.1 Introduction

Determining the in situ density of non-cohesive granular soils is an ongoing challenge for geotechnical engineers, resulting in the development of several methods. The Perth Sand Penetrometer (PSP) test is a relatively quick, inexpensive method of checking the in situ density of these types of soils when the depth of exploration is shallow. It has been used in the Perth construction industry for approximately 50 years to check foundation compaction. MRWA currently accepts PSP testing as proof of construction compliance for earthworks and subgrade construction; however, there is no published specification or guidance on the use of the test method as a QC tool.

The current PSP testing procedure, literature and case studies of past method specification submissions to MRWA are discussed in the following sections.

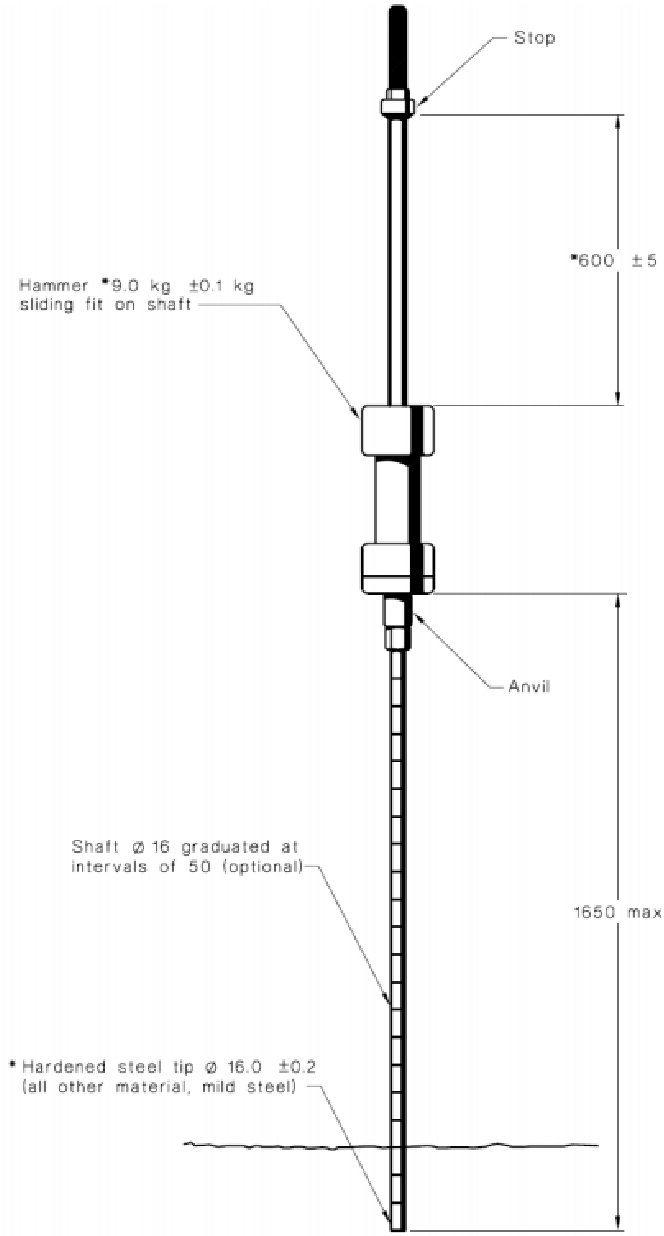
4.2 Perth Sand Penetrometer

The procedure for determining the resistance of soil using the PSP is outlined in AS 1289.6.3.3 *Methods of testing soils for engineering purposes – soil strength and consolidation tests: determination of the penetration resistance of a soil – Perth sand penetrometer test*. The procedure is as follows:

- Excavate to the level to be tested and remove material such as crushed rock or gravel, which is too hard to penetrate with the PSP or may damage the equipment.
- Measure the depth from the surface level to the upper surface of the layer to be tested to the nearest 10 mm.
- Hold the PSP vertical with the tip on the surface of the layer to be tested and tap the hammer on the anvil until a penetration of 150 mm is achieved using a 16 mm blunt ended steel rod.
- Raise the 9 kg hammer to a stop and then allow it to fall freely onto the anvil from a height of 600 mm, and count the number of blows required to drive the PSP to a depth of 300 mm (total penetration 450 mm).
- The penetration resistance (N_p) is calculated by totalling the number of blows to produce 300 mm further penetration after the initial 150 mm.

A schematic of the PSP, showing the standard dimensions and masses is presented in Figure 4.1.

Figure 4.1: Schematic of PSP



Source: AS 1289.6.3.3.

4.2.1 Applicable Materials

The PSP is typically used on two types of materials: Perth sands and select fill material. The required grading envelopes for Perth sands and MRWA select fill, as stated in Specification 302 *Earthworks* (Main Roads Western Australia 2015) are presented in Table 4.1 and Table 4.2, respectively.

Table 4.1: Imported material for embankments inclusive of subgrade 'Perth Sand' typical grading envelope

AS sieve size (mm)	% passing by mass
37.5	90–100
2.36	30–100
0.075	1–10

Source: MRWA (2015).

Table 4.2: Select fill grading envelope

AS sieve size (mm)	% passing by mass
37.5	100
19.0	80–100
9.5	60–100
4.75	45–100
2.36	30–100
1.18	20–100
0.425	5–100

Source: MRWA (2015).

4.3 Nuclear Density Method

As discussed previously in Section 2.3.2, MRWA Test Method WA 324.2 describes the procedure for the in situ determination of the dry density of materials with less than 20% retained on the 37.5 mm sieve by the use of a NDM in direct transmission mode. The test is carried out by placing the NDM on the surface of material and inserting the NDM probe into a pre-drilled hole. Gamma radiation is emitted from the device through the material to the sensor, providing an average density measure of the material between the two points. The standard depth of measurement for this method in earthworks can be up to 300 mm below ground level (bgl).

4.4 Literature Review

Glick and Clegg (1965) described the development and calibration of a falling weight penetrometer, suitable for rapidly assessing the in situ density of sands in the Perth areas of Western Australia and the Swan Coastal Plain, which would go on to be known as the PSP. The PSP was developed as a modified version of the Scala Penetrometer, using a 9 kg drop weight to hammer a 16 mm diameter steel rod into the ground. The main difference is that the tip of the PSP is blunt, whereas the tip of the Scala Penetrometer is conical.

Glick and Clegg (1965) found that after an initial penetration of between 150 mm and 200 mm, the relationship between depth and blow count was linear to the depth investigated (760 mm) for a layer of dry sand of uniform density under laboratory conditions. The results of testing were presented as a typical plot, stating that generally, for all moisture contents, similar linear relationships were observed to the depth investigated. Notably, Glick and Clegg (1965) stated that as soil is a variable material, tests must be conducted to ensure uniformity for PSP blow counts to be accepted as useful guides to design or control.

A study by Clegg (1979) on the influence of sand type, depth and moisture content of PSP results found that sand type had the biggest impact on the PSP. Furthermore, the effect of moisture content apart from saturated, submerged or completely dry was minimal. In terms of calibration for the standard test interval (between 150 mm and 450 mm), Clegg (1979) recommended that

8 blows/300 mm was the typical result for good compaction. The study indicated that, with increased depth beyond the standard test interval, the soil would have an increased penetration resistance due to overburden stress.

The effect of depth on the results of the PSP was investigated by Coman-Walton and Fahey (2009) using both laboratory and field testing. The study concluded that, contrary to Glick and Clegg's (1965) findings, there was no universal relationship between blow counts and depth for any given relative density. It was postulated that the laboratory tests reported by Glick and Clegg were deficient in terms of accurately representing the effect of burial depth in situ, which may have been related to the effect of confining pressure on tip resistance. As such, Coman-Walton and Fahey (2009) concluded that the use of the PSP to investigate the degree of compaction for depths other than the standard of between 150 mm and 450 mm depth interval specified in AS 1289.6.3.3 was unreliable without such site-specific calibration.

The applicability of the PSP to determine the engineering properties of sands, and the repeatability of the test method, was studied by Mohammadi (2016). The study concluded that the PSP results showed good correlation (> 90%) with relative density, modulus of elasticity and shear modulus based on testing on poorly graded sandy soils in Tehran, Iran. Furthermore, Mohammadi (2016) concluded that the results of the PSP test for five relative densities were repeatable.

4.5 Case Studies – Past Method Specification Submissions

Method specifications are developed by contractors and submitted to MRWA with the aim of decreasing the frequency of nuclear density testing by calibrating the PSP to in situ field density of a specific material. These submissions often include various items of information relating to the project and a description of the material and application for which the method specification has been developed. Roller information and number of passes may also be included.

The calibration of the PSP to ensure density for the chosen site-specific activity and material is also included and typically includes, at a minimum, PSP blows/300 mm between 150–450 mm below ground level (bgl) and the corresponding nuclear density ratio between 0–300 mm bgl at several test locations. This data is then used to infer the minimum number of PSP blows/300 mm between 150–450 mm bgl required to meet the field density requirements.

As there is currently no framework or guidance for the development of method specification submissions, submission contents vary and often do not include the necessary information required to ensure an accurate calibration. This may lead to misinterpretation of the calibration data to infer the minimum number of PSP blows/300 mm.

The following sections detail seven past method specifications which have been submitted to MRWA for various projects. The calibration method and corresponding data in addition to the inferred PSP blow/300 mm requirement made by the contractor is presented along with other information supplied within the submission. A revised data analysis is also undertaken to ensure consistency of the calibration data assessments and to ensure the data has been interpreted correctly.

Issues and highlights of each of the submission are also presented in order to understand what method submissions often lack and what makes a good submission with a thorough calibration. The case studies have subsequently been used to develop a draft method specification framework to ensure future submissions, including the necessary information, and that the calibration data is assessed correctly.

4.5.1 Armadale Road Upgrade

Introduction

As part of the Armadale Road Upgrade an Alliance developed and submitted a compaction method specification in which a PSP could be utilised to reduce the frequency of nuclear density testing. The document was authored by Kit Wu of the Metropolitan Road Improvement Alliance, assigned document number 07-7000-030-GT-PP-0028-0 and is dated 3 July 2018.

The PSP correlation presented was intended for the construction of bulk earthworks such as embankment construction. It was calibrated for 450 mm thick lifts using the proposed fill material sourced from WA sands which comprise yellow, medium-grained ‘Perth’ sand. It was specifically stated that a new compaction trial would be undertaken where a change in material source or type occurred.

The density requirement for the bulk earthworks was specified at 95% modified maximum dry density (MMDD).

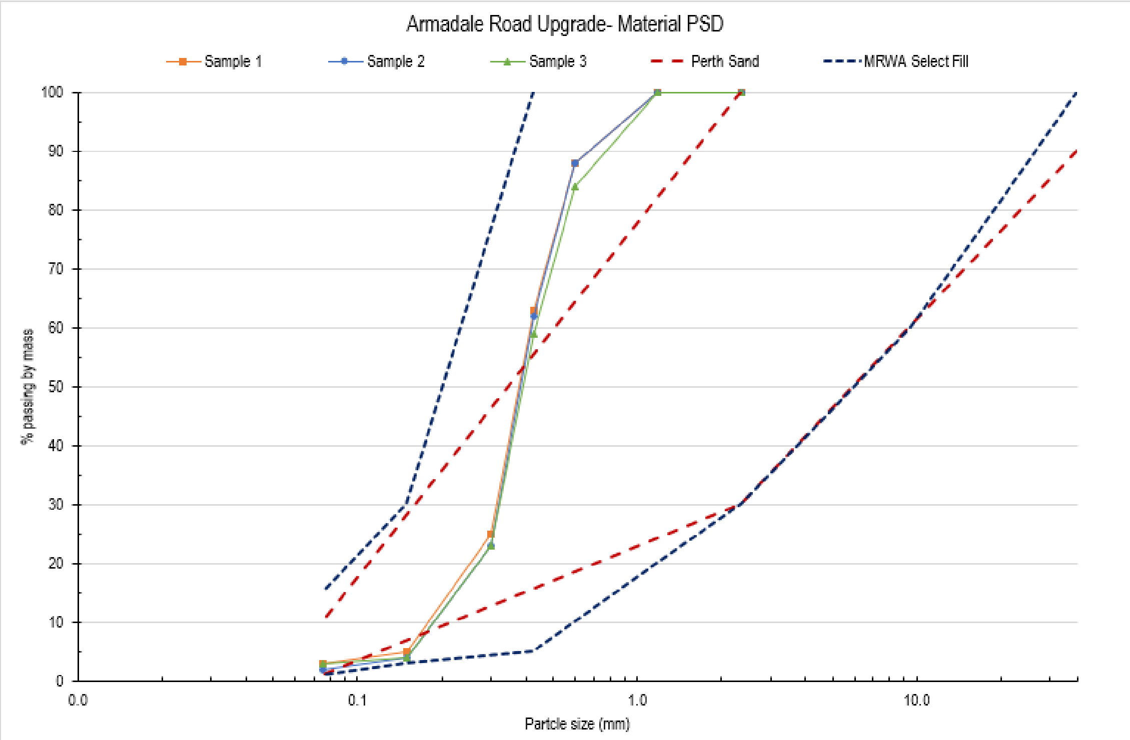
Material

Particle size distribution (PSD) testing of the material was undertaken and compared to the definition of a Perth sand as embankment fill as per MRWA Specification 302 *Earthworks* (Main Roads Western Australia 2015). The gradings are compared in Table 4.3. The gradings of each of the materials used in the calibration trial, in addition to the typical Perth sand grading and the MRWA select fill grading envelope, as per Specification 302 and as discussed previously in Section 4.3, are shown in Figure 4.2.

Table 4.3: Armadale Road Upgrade – sand PSD test results

AS sieve size (mm)	% passing by mass		
	Sample 1	Sample 2	Sample 3
2.36	100	100	100
1.18	100	100	100
0.6	88	88	84
0.425	63	62	59
0.3	25	23	23
0.15	5	4	4
0.075	3	2	3

Figure 4.2: Armadale Road Upgrade – grading plot with specification envelopes



Calibration method

For the calibration, a specified trial area of approximately 6000 m^2 was designated in the vicinity of the project site with a width that allowed two roller widths with sufficient roller overlap.

The process anticipated for the construction of the project embankments was mirrored for the calibration trial and included the following:

1. Placement of a 550 mm thick loose lift.
2. Passage of of two 15 kL water trucks (30 kL total) to moisture condition the soils (targeting ±10% of OMC), with a water application rate of about 150 L/m^2.
3. Compaction using six passes of a 20 ton vibratory smooth drum roller (one pass constituting 'up and back').

The calibration process comprised NDM and PSP testing at six staggered locations after each two passes of the roller. This was repeated until the total passes equalled six.

The PSP testing was undertaken between a depth of 150 mm and 450 mm bgl with blows/50 mm recorded as per AS 1289.6.3.3. The blow count per 300 mm was then calculated for each test site.

NDM testing was undertaken adjacent to the PSP at the standard depth between 0 mm and 300 mm bgl, and between 150 mm and 450 mm bgl. MMDD tests were undertaken at a ratio of 2 MMDD tests for every 6 NDM tests.

Calibration data

Table 4.4 presents the collected data from the calibration test site. The calibration plot as supplied by the contractor is presented in Figure 4.3.

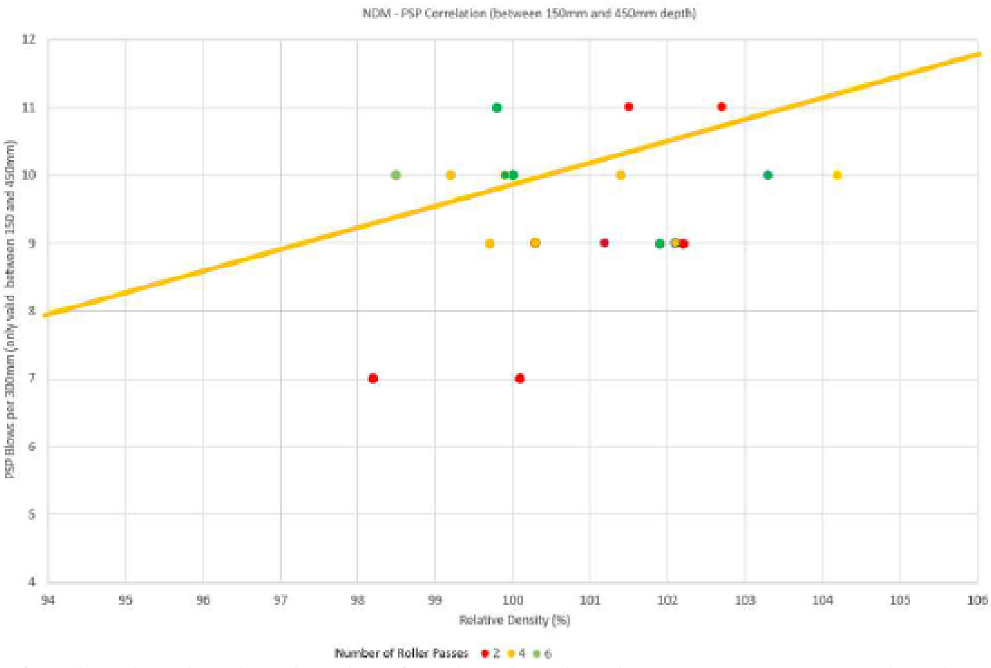
Table 4.4: Armadale Road Upgrade – contractor supplied calibration data

Roller passes (no.)	Test	Depth bgl (mm)	Site 1	Site 2	Site 3	Site 4	Site 5	Site 6
2	PSP blows/300 mm	150–450	7	7	9	9	11	11
	NDM dry density (%)	0–300	96.6	97.8	100.8	99.3	100.8	100.7
		150–450	98.2	100.1	102.2	101.2	102.7	101.5
4	PSP blows/300 mm	150–450	9	10	10	9	9	10
	NDM dry density (%)	0–300	103.1	98.3	101.3	100.4	99.2	101.3
		150–450	99.7	99.2	101.4	100.3	102.1	104.2
6	PSP blows/300 mm	150–450	10	11	9	10	10	10
	NDM dry density (%)	0–300	97.7	100.6	100.9	98.1	94.4	101.3
		150–450	100.0	99.8	101.9	99.9	103.3	98.5

It was noted that after six passes Site 5 returned a density lower than 95% MMDD. However, the characteristic density for this sample of six tests was calculated as 97.2% MMDD using a k value of 0.68 as per ERN8 *Statistically based quality control for density in road construction* (Main Roads Western Australia 2008). It was therefore not considered a failed test and would not require reworking.

The submitted method specification suggested 8 blows/300 mm between 150 mm and 450 mm bgl to achieve 95% MMDD.

Figure 4.3: Armadale Road Upgrade – contractor supplied calibration data plot



Method specification recommendations

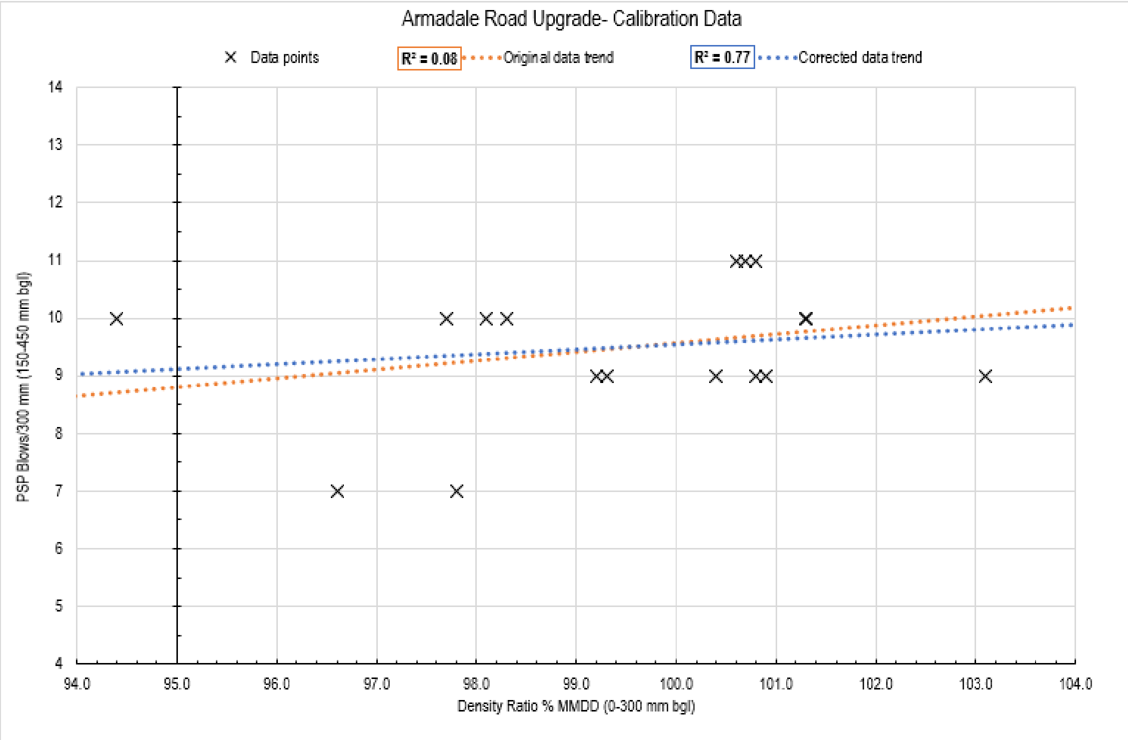
It was recommended that four passes of the roller be undertaken, and 8 blows (between 150 mm and 450 mm depth) of the PSP was chosen to correlate with 95% MMDD.

It was also recommended that, in order to check the top 150 mm of each lift, PSP testing of the subsequent lifts was to be extended to record the number of blows between 450 mm to 750 mm. A blow count/300 mm of 12 was said to correlate with 95% MMDD at this depth.

Revised data analysis

An alternative analysis of the PSP and density data was undertaken. Figure 4.4 compares the NDM data from the standard test depth of between 0 and 300 mm bgl with the PSP blows/300 mm for the standard test depth of between 150 mm and 450 mm bgl. Both an uncorrected and corrected linear trend line have been included to demonstrate the similarity in the trend positions and the difference in R^2 for both. The corrected trend line includes a standardised data point of 0 blows/300 mm and 0% density ratio (i.e. a y-axis intercept of 0).

Figure 4.4: Armadale Road Upgrade – revised calibration data plot



From this plot, a rounded number of 10 blows/300 mm was inferred to correlate with required field density of 95% MMDD.

Issues with contractor-developed method specification

- The statistical correlation coefficient was very low and may only be applicable to setting a minimum PSP value.
- The recommended blows/300 mm calculated in the method specification are lower than those inferred from Figure 4.4.
- Blows/300 mm between 450 mm and 750 mm depth are also supplied in order to test the top 150 mm of each previous lift however the method of determining this number is not described.

Highlights

- The calibration used a separate, dedicated test area.
- Several material PSDs are supplied to clearly classify the material for which the calibration was undertaken for future reference.
- Presentation of the calibration data is easy to understand and does not include unnecessary information.
- Ongoing PSD testing frequencies are specified to ensure ongoing material conformance.
- Ongoing MC and OMC testing frequencies are specified to ensure ongoing conformance.
- There are clear instructions for the construction process including water application rate and minimum number of roller passes.
- Ongoing nuclear density testing frequencies to ensure ongoing density compliance is documented as every third lot or lift (whichever is more stringent) starting with the initial lot.
- In the event of a failed nuclear density test or a change in material, the calibration is to be re-assessed.
- All testing is to be completed before the placement of the next lift.
- All test certificates from the calibration are included in addition to photographs.

4.5.2 Mitchell Freeway Extension

Introduction

As part of the Mitchell Freeway extension between Burns Beach Road and Hester Avenue, a contractor developed a method specification in which a PSP can be utilised to reduce the frequency of NDG testing for field density QC. The document was authored by Declan Murphy of Leighton Contractors, assigned document number WO1000-CS-CMS-8005-REV01 and is dated 8 October 2015.

The PSP correlation presented was intended for use in general bulk earthworks which uses the site-won sand. These activities were said to include:

- embankment fill lifts
- drainage backfill areas (including pits)
- reinstatement/protection of concrete structures (e.g. water main)
- backfilling street-light pole box-outs prior to streetlight installation
- backfill of bridge abutment, terrace walls and pier box-out areas
- mechanically stabilised earth (MSE) wall backfill areas.

The calibration was based on 300 mm thick lifts using the proposed fill material sourced from the project site which comprises yellow sand. It was stated that the correlation developed should relate only to the site-won sand. No allowance for ongoing material compliance during construction was stated.

The density requirement for the bulk earthworks was specified at 95% MMDD.

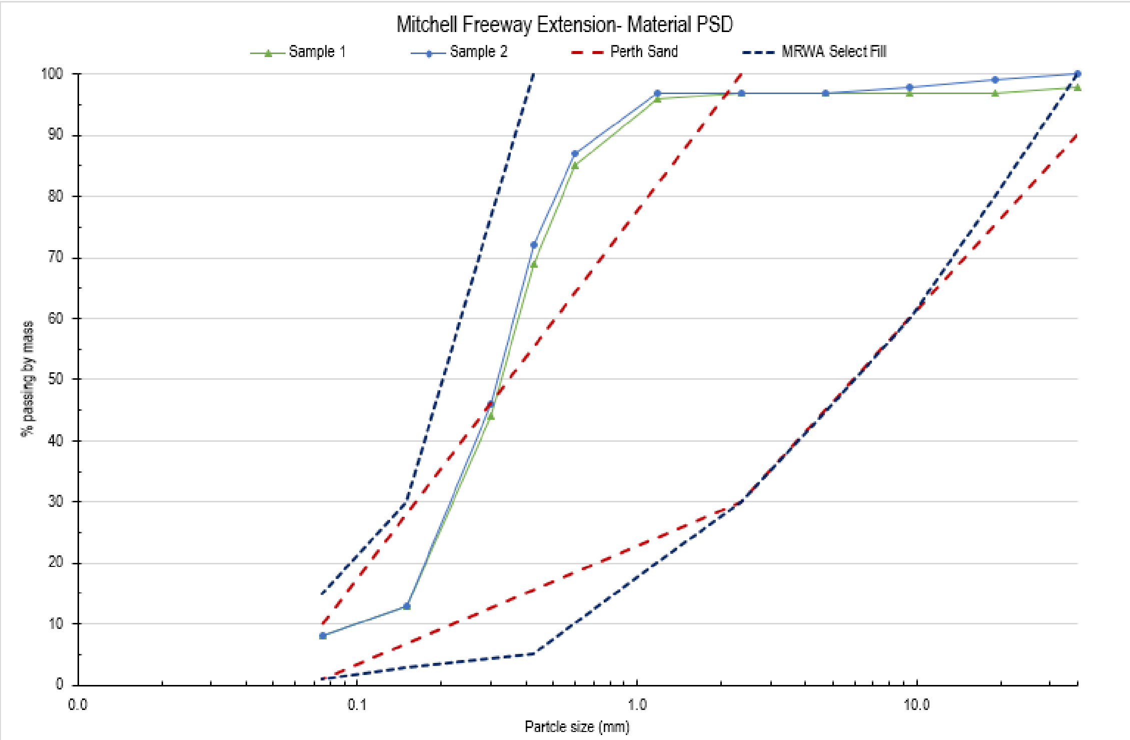
Material

PSD testing of the material was undertaken and compared to the definition of a Perth sand as embankment fill as per MRWA Specification 302 *Earthworks* (Main Roads Western Australia 2015). The grading data is shown in Table 4.5. The grading plots of the tested material from the calibration trial, the typical Perth Sand grading and the MRWA select fill grading envelope, as per Specification 302 and as discussed previously in Section 4.3, are compared in Figure 4.5

Table 4.5: Mitchell Freeway Extension – sand PSD test results

AS sieve size (mm)	% passing by mass	
	Sample 1	Sample 2
300	100	100
75	100	100
37.5	98	100
19	97	99
9.5	97	98
4.75	97	97
2.36	97	97
1.18	96	97
0.6	85	87
0.425	69	72
0.3	44	46
0.15	13	13
0.075	8	8

Figure 4.5: Mitchell Freeway Extension – grading plot with specification envelopes



Calibration method

The construction of a required embankment was used for the calibration trial. A total of six lifts were undertaken corresponding to 36 NDM and PSP results. Density/moisture relationship tests (MMDD/OMC) were undertaken at a ratio of 2 MMDDs for every 6 NDMs.

The process anticipated for construction of the project embankments was mirrored for the calibration trial and included the following:

1. Wet the surface using multiple passes.
2. Scarify to a depth of 300 mm using a CAT140H Grader.
3. Six to eight passes of a 12 t Hamm smooth drum roller set to medium to high vibration (approximately 50 Hz) with a 1.89 mm vibration amplitude travelling at approximately 5 km/h.
4. NDM's at 300 mm below ground level and moisture content (MC) tests in accordance with WA 110.1, WA 134.1, WA 136.1 and WA 324.2.
5. PSP test adjacent to each nuclear density meter tests in accordance with AS 1289.6.3.3.

The calibration process comprised NDM, MC and PSP testing at six staggered locations after six to eight passes of the roller.

The PSP testing was undertaken between a depth of 150 mm and 450 mm bgl with blows/50 mm recorded as per AS 1289.6.3.3. The blow count per 300 mm was then calculated for each test site. NDM testing was undertaken adjacent to the PSP at the standard depth, between 0 mm and 300 mm bgl.

Calibration data

Table 4.6 presents the simplified collected data from the calibration test site. The data plot supplied by the contractor which is presented in Figure 4.6. Values in bold and italics are below the requirement for 95% MMDD.

Table 4.6: Mitchell Freeway Extension – contractor supplied calibration data

Site ID	Lift 1		Lift 2		Lift 3		Lift 4		Lift 5		Lift 6	
	PSP blows(1)	DR(2)	PSP blows	DR	PSP blows	DR	PSP blows	DR	PSP blows	DR	PSP blows	DR
Site 1	13	95.7	8	***94.8***	11	100.9	12	99.4	10	100.5	13	97.1
Site 2	14	97.8	11	96.3	14	99.4	13	99.9	9	97.4	13	95.6
Site 3	12	***94.0***	13	98.4	16	100.4	12	99.7	9	99.0	13	96.1
Site 4	11	97.2	14	95.2	10	97.0	11	101.4	10	98.0	13	97.7
Site 5	12	98.1	11	99.1	11	95.9	8	99.2	11	99.5	9	99.5
Site 6	10	98.1	10	95.6	14	99.4	9	99.8	9	98.6	9	95.7

Notes:

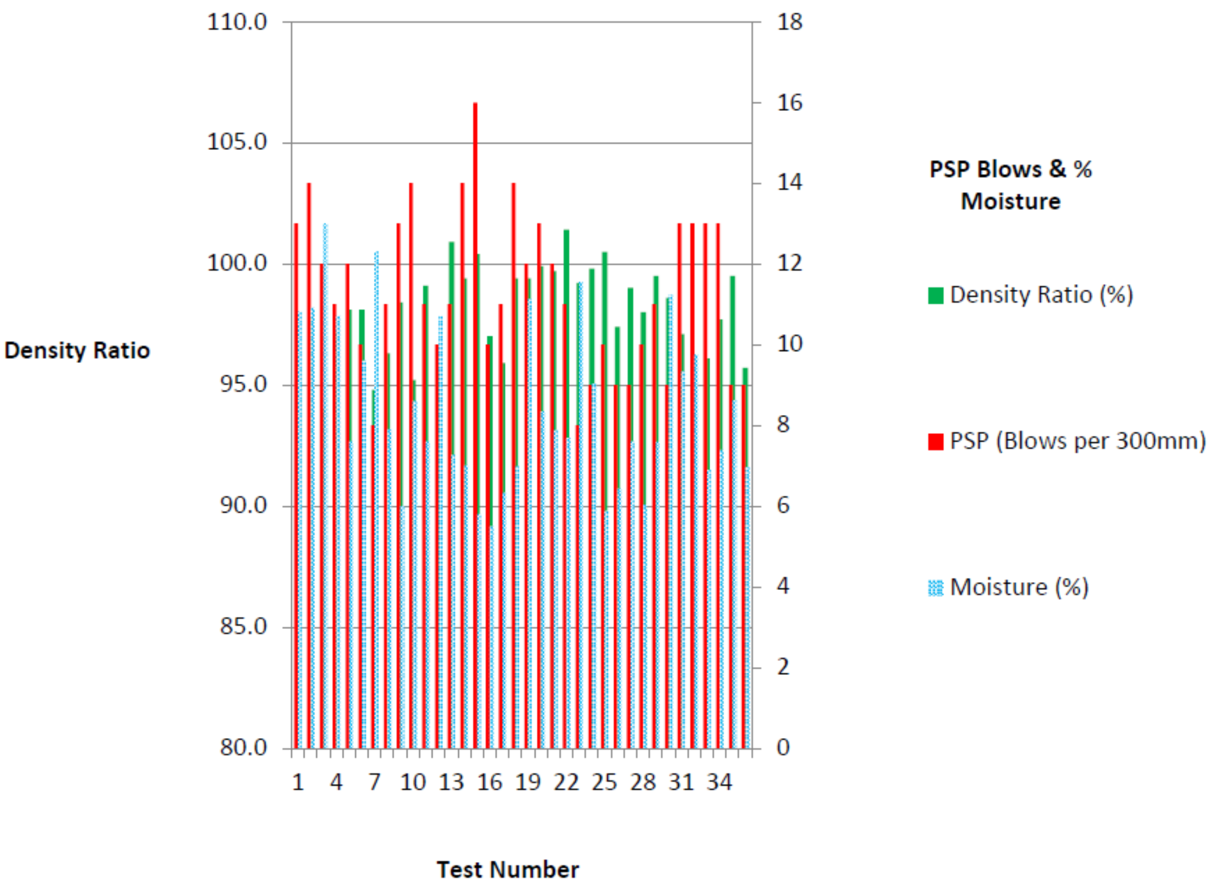
1 PSP blows – PSP blows/300 mm; test depth 150–450 mm bgl.

2 DR – Nuclear density ratio; test depth 0–300 mm bgl.

It was noted that Site 3 of Lift 1 and Site 1 of Lift 2 returned a density lower than 95% MMDD. However, the characteristic density for the sample of six tests per lift was calculated as 95.4% MMDD and 95.1% MMDD for Lift 1 and Lift 2 respectively using a k value of 0.91 as per ERN8

Statistically based quality control for density in road construction (Main Roads Western Australia 2008). They were therefore not considered a failed test and would not require reworking.

Figure 4.6: Mitchell Freeway Extension – contractor supplied data plot



The submitted method specification suggested 11 blows/300 mm between 150 mm and 450 mm bgl to correlate to 95% MMDD.

Method specification recommendations

Recommendations suggest that an average penetration rate of 27.27 mm/blow or less is required to achieve the embankment fill compaction requirement. For application in the field, this would correspond to 11 blows per 300 mm or more. A suitable method for undertaking this task was as follows:

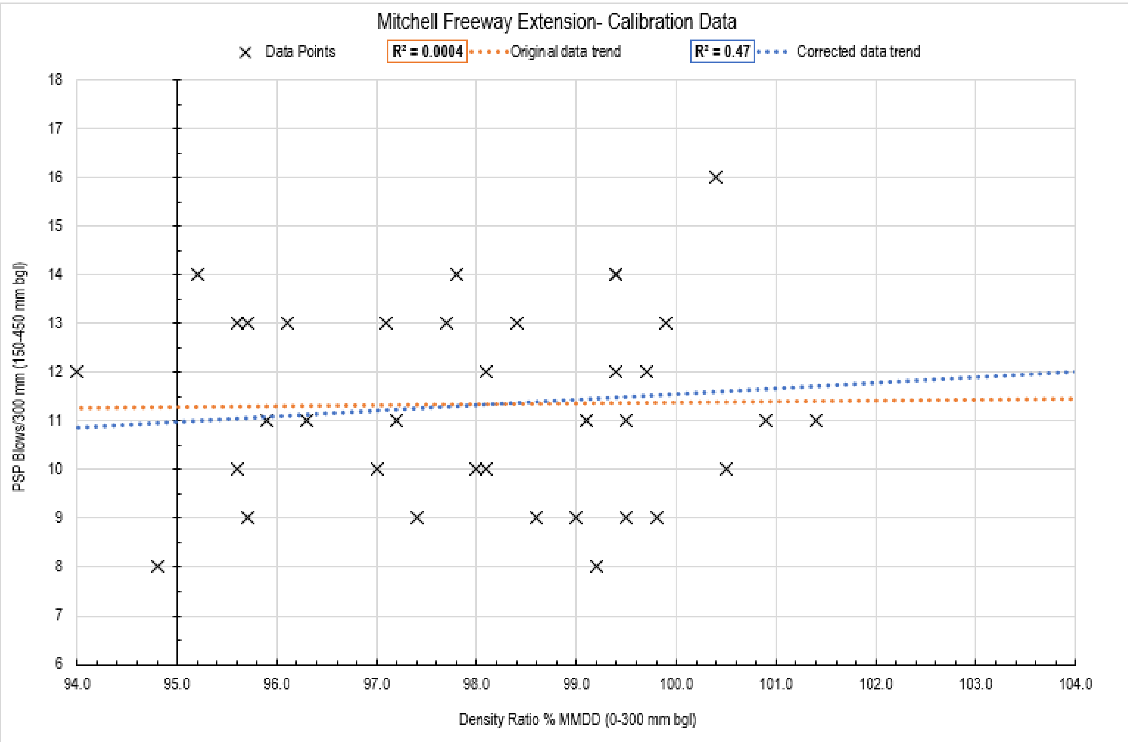
- Take a Perth Sand Penetrometer that complies with AS 1289.6.3.3.
- Hold the penetrometer vertical with the tip of the surface of the layer to be tested and tap until a penetration of 150 mm is achieved.
- Count and record the number of blows required to achieve 300 mm penetration (i.e. between 150 mm and 450 mm below surface).
- If 11 or more blows are required for a 300 mm layer, a DDR of 95% MMDD has been achieved.

It was also recommended that NDM's be used to confirm that the PSP compaction testing conforms to NDM results for every third embankment fill lift.

Revised data analysis

An alternative analysis of the PSP and density data was undertaken. Figure 4.7 compares the NDM data from the standard test depth of between 0 mm and 300 mm bgl plotted against the PSP blows/300 mm for the standard test depth of between 150 mm and 450 mm bgl. Both an uncorrected and corrected linear trend line have been included to demonstrate the similarity in the trend positions and the difference in R^2 for both. The corrected trend line includes a standardised data point of 0 blows/300 mm and 0% density ratio.

Figure 4.7: Mitchell Freeway Extension – revised calibration data plot



From this plot, a rounded number of 11 blows/300 mm was inferred to correlate with required field density of 95% MMDD.

Issues with contractor-developed method specification

The method specification presented by Leighton Contractors has the following issues:

- The table and graphical representation of the calibration data is confusing and includes irrelevant information.
- The statistical correlation coefficient is very low and may only be applicable to setting a minimum PSP value.
- The graphical representation of the PSP and density ratio used to calculate the recommended 11 blows/300 mm (Figure 4.6) is invalid and is entirely dependent on the chosen axis scales.

- There is no ongoing requirement to check material conformity to that used in the calibration trial.
- There are no ongoing requirements to check MC and MMDD/OMC relationships.
- There is no guidance in the event of a fail nuclear density test or a change in material.

Highlights

- Two PSD test certificates are included in the submission.
- The calibration activity is undertaken on a separate test area and covers various embankment lifts.
- There are clear instructions for the compaction process including roller passes, vibration requirements and roller speed.
- Ongoing nuclear density testing frequencies to ensure ongoing density compliance is documented as every third lift.
- All test certificates from the calibration are included.
- The recommended blows/300 mm calculated in the method specification are the same as those inferred from Figure 4.7.

4.5.3 Northlink 1 – Grey Sand

Introduction

As part of the Northlink 1 Southern Section between Guildford Road to Reid Highway, a contractor developed a method specification in which a PSP can be utilised to reduce the frequency of nuclear density testing for field density QC. The request for information was authored by Grant Coombs of John Holland Contractors, assigned document number JH-FRM-DES-002-02 and is dated 6 December 2016.

The PSP correlation presented was intended for the use in bulk earthworks, specifically structural backfill and embankment construction.

The calibration was based on a single 300 mm thick lift using the proposed fill material sourced from the project site which comprised grey sand. It was stated that the correlation developed should relate only to the site-won grey sand. Visual inspection to ensure the material was typical of the project was allowed for, in addition to ongoing dry density ratio and PSD testing every fifth lift, or every 1.5 m in the section.

The density requirement for the bulk earthworks was specified at 95% MMDD.

Material

No PSD test certificates were provided with the submission.

Calibration method

The calibration process was comprised NDM and PSP testing at various frequencies after each successive pass of the roller, as summarised in Table 4.7.

The PSP testing was undertaken between a depth of 150 mm and 450 mm bgl with blows/50 mm recorded as per AS 1289.6.3.3. The blow count per 300 mm was then calculated for each test site.

NDM testing was undertaken adjacent to the PSP at the standard depth between 0 mm and 300 mm bgl. A total of three MMDD/OMC tests were undertaken.

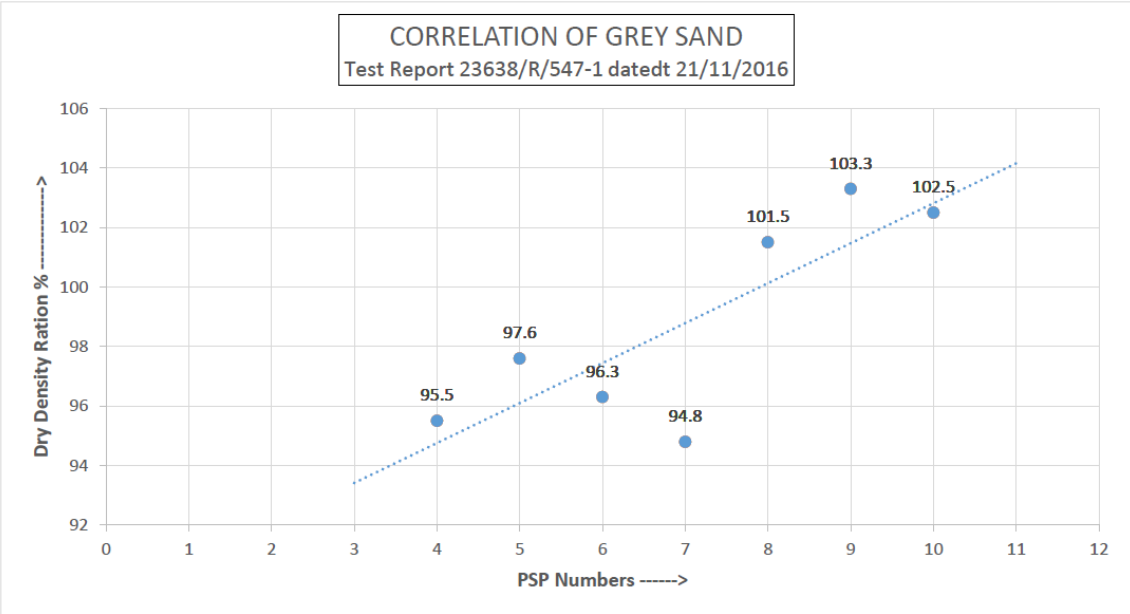
Calibration data

Table 4.7 presents the data collected from the calibration test site. The calibration plot as supplied by the contractor is presented in Figure 4.8.

Table 4.7: Northlink 1 – contractor supplied calibration data

Roller passes (no.)	Test	Depth (mm, bgl)	Site 1	Site 2	Site 3	Site 4
Initial (0)	PSP	150–450	4	–	–	–
	NDM	0–300	95.5	–	–	–
1	PSP	150–450	6	–	–	–
	NDM	0–300	96.3	–	–	–
2	PSP	150–450	9	7	8	5
	NDM	0–300	103.3	94.8	101.5	97.6
3	PSP	150–450	10	–	–	–
	NDM	0–300	102.5	–	–	–

Figure 4.8: Northlink 1 – contractor supplied data plot



Method specification recommendations

The recommended construction process, as detailed in document no. NLS-JHG-RFI-150 Rev C and specified for use with the grey sand, is as follows:

1. Visually inspect material to verify the material is sand typical of the project, and proven to meet 20% or less by mass of material retained on the 37.5 mm AS sieve.

2. Place material to a loose thickness of 350–370 mm to achieve a maximum compacted thickness of 300 mm.
3. Four passes (one direction is one pass) of the watercart to meet targeted OMC.
4. Compact with at least one 15 t smooth drum roller set to high vibration and minimum 10% overlap for a minimum of eight passes.
5. Conduct moisture content testing to demonstrate that the characteristic MC ratio is between 70–110%.
6. Conduct PSP testing at six random locations in accordance with AS 1289.6.3.3, achieving 6 blows per 300 mm between 150–450 mm to ensure required field density.

Based on the correlation graph and line of best fit presented in Figure 4.8, it was proposed that six blows of a PSP corresponded to the required dry density ratio of 95% MMDD or greater.

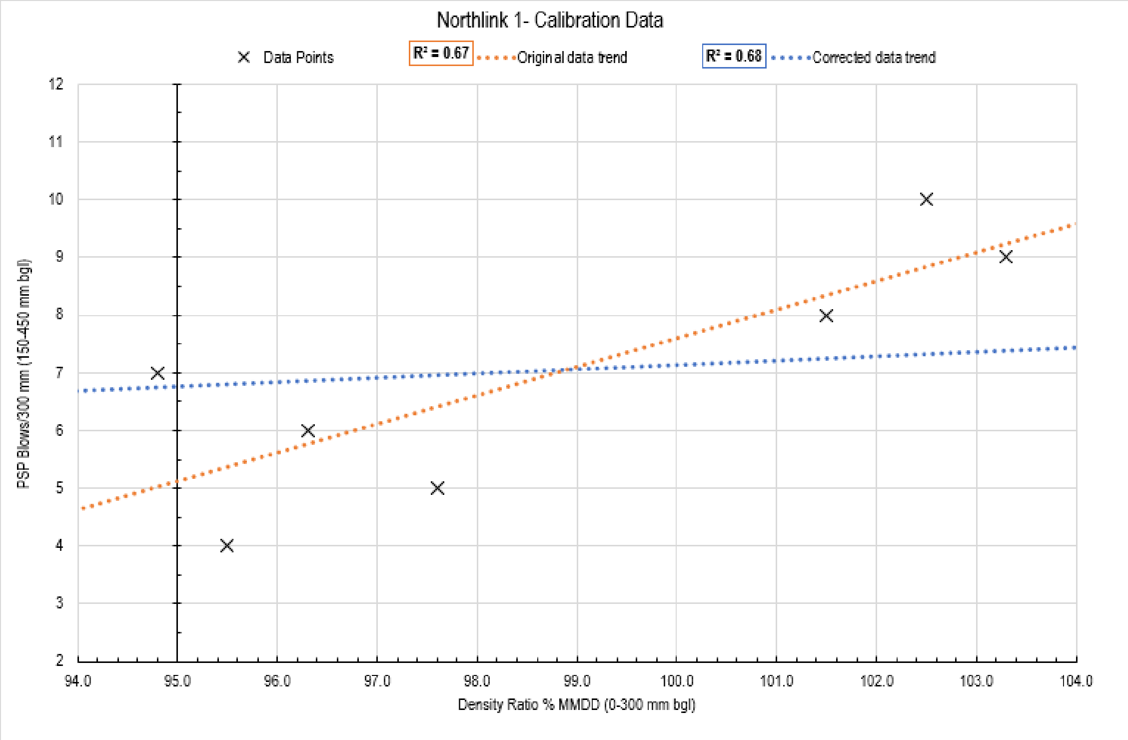
It was also recommended that dry density ratio (WA 134.1), and PSD (WA 115.2) (MRWA 2011d) testing should be undertaken at every fifth lift, or every 1.5 m in the section of construction and include the first and last lift, to demonstrate that the method is continuing to achieve the required density.

If a lot fails when tested by the PSP or NDM, that lot shall be re-worked and tested by a NDM. If the next three consecutive lots tested by the NDM are compliant the method specification process may resume.

Revised data analysis

An alternative analysis of the PSP and density data was undertaken. Figure 4.9 presents the NDM data from the standard test depth of between 0 mm and 300 mm bgl plotted against the PSP blows/300 mm for the standard test depth of between 150 mm and 450 mm bgl. Both an uncorrected and corrected trend line have been included to demonstrate the similarity in the trend positions and the difference in R^2 for both.

Figure 4.9: Northlink 1 – revised calibration data plot



From this plot, a rounded number of 7 blows/300 mm has been inferred to correlate with required field density of 95% MMDD. The submitted method specification suggested 6 blows/300 mm to correlate to 95% MMDD.

Issues with contractor-developed method specification

The method specification presented by John Holland has the following issues:

- No material PSD certificates were included in the submission.
- The details of the calibration method were not provided.
- The recommended blows/300 mm calculated in the method specification are lower than those inferred from Figure 4.9.
- The number of data points for each successive roller pass was not consistent.
- The number of roller passes is poorly defined; initial (no passes) field density was in compliance with the required field density.

Highlights

Highlights from the method specification include the following:

- There are clear recommendations for the compaction process, including roller passes and water truck passes.
- There is an ongoing requirement to check material conformity with dry density ratio (WA 134.1), and PSD (WA 115.2), undertaken at every fifth lift, or every 1.5 m in the section of construction and include the first and last lift.

- If a lot fails, the next three consecutive lots tested by NDM must be compliant, otherwise the method specification process may not resume.

4.5.4 Nicholson Road

Introduction

During construction of the Nicholson Road upgrade project, a contractor developed a method specification in which a PSP can be utilised to reduce the frequency of nuclear density testing for field density QC. The method specification was authored by CPB Contractors and is dated 27 June 2017.

The PSP correlation presented was intended for the construction of bulk earthworks such as embankment fill lifts and drainage backfill areas. Calibration was completed for 450 mm thick lifts in accordance with AS 1289.6.3.3.

Sands encountered include grey/brown sand at 0.4 m to 2.0 m depth, and black Bassendean sands from 1.5 m to 4.5 m depth. The grey/brown sand was typically used on the project for backfilling drainage lines and service trenches following protection works whereas the black sand was used in the lower lifts of the embankment material. It was stated that materials falling outside the sand grading bracket or containing oversize particles will prevent the use of the PSP, and an additional method specification using the DCP was proposed.

The density requirements for the bulk earthworks were specified at 95% MMDD.

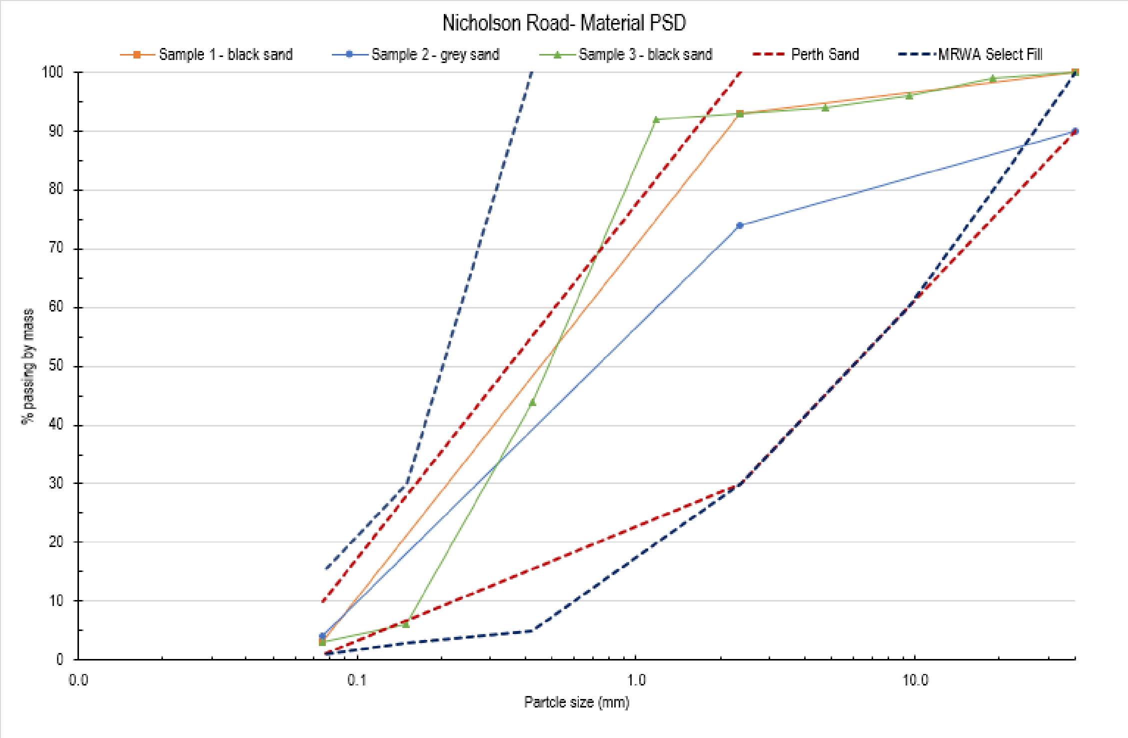
Material

PSD testing was undertaken to classify the proposed fill material sourced from the project site. This was undertaken in accordance with both the Perth sand grading and the select fill grading, as specified in MRWA Specification 302 *Earthworks* (Main Roads Western Australia 2015). The gradings results are summarised in Table 4.8, whilst Figure 4.10 displays plots of the tested materials in addition to the typical Perth sand grading and the MRWA select fill grading envelope.

Table 4.8: Nicholson Road project – sand PSD test results

AS sieve size (mm)	% passing by mass		
	Sample 1 (black sand – Perth sands)	Sample 2 (grey/brown sand – Perth sands)	Sample 3 (black sand – select fill)
37.5	100	90	100
19.0	–	–	99
9.5	–	–	96
4.75	–	–	94
2.36	93	74	93
1.18	–	–	92
0.425	–	–	44
0.15	–	–	6
0.075	3	4	3

Figure 4.10: Nicholson Road project – grading plot with specification envelopes



Calibration method

The correlation for the site material was developed by completing parallel PSP and NDM testing on two lots on the project. The method included the following:

1. Work lot until compaction has been achieved, recoding layer depth. The lot may be compacted by conditioning to OMC and:
   - Completing eight passes with a 12 t smooth drum roller set to high oscillation (suitable for foundation preparation, structural foundations, embankment construction and structural backfill > 3 m from structure).
   - Completing ten passes with a 2 t mini roller (suitable for trench backfill, structural foundations and structural backfill > 3 m from structure).
   - Completion 12 passes with a 700 kg plate compactor (suitable for drainage bedding, trench backfill, structural backfill > 3 m from structure).
2. Conduct NDM testing adjacent to the PSP test sites and take moisture samples in accordance with WA 134.1, WA 110.1 and WA 133.1. Testing is completed at the maximum probe depth of 300 mm.
3. Compare the PSP results (blows per 300 mm displacement) witht the dry density ratio and with a trend line.

PSP testing was undertaken between a depth of 150 mm and 450 mm bgl with blows/50 mm recorded as per AS 1289.6.3.3. The blow count per 300 mm total displacement was then calculated for each test site.

Calibration data

Table 4.9 presents the contractor-supplied calibration data for the Nicholson Road project.

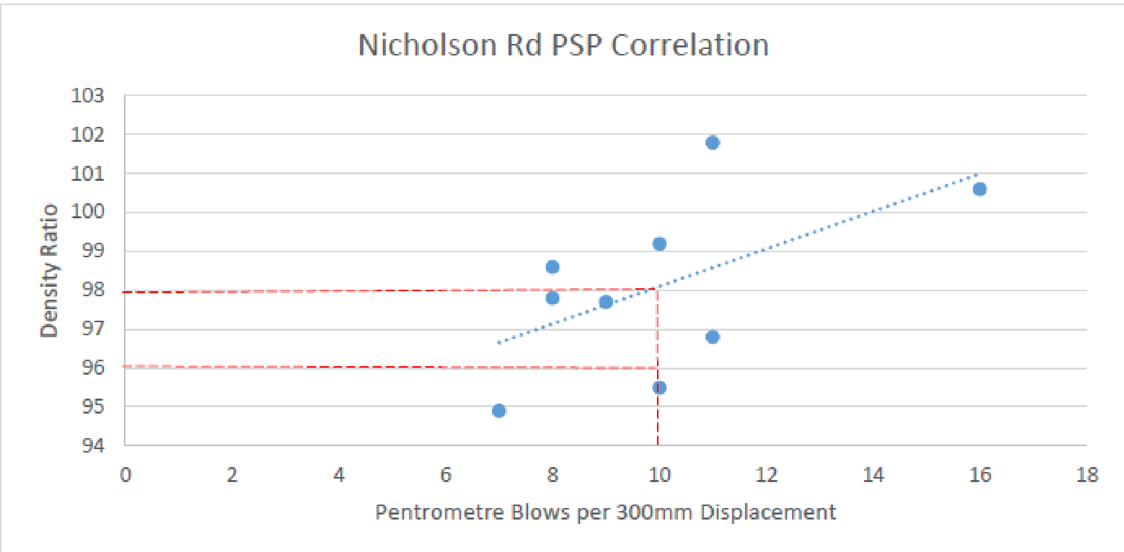
Table 4.9: Nicholson Road project – contractor-supplied calibration data

Test site	Blow/300 mm displacement	Dry density ratio (%)
Black sand		
1	8	97.8
2	11	96.8
3	8	98.6
4	7	94.9
5	11	101.8
6	10	95.5
Grey/brown fill sand		
3	10	99.2
4	9	97.7
6	16	100.6

Notably, the dry density ratio obtained at black sand Site 4 returned a value lower than the specified 95% MMDD. However, the characteristic dry density ratio for this sample of six tests was calculated as 96% MMDD using a value of k of 0.68 in accordance with ERN8 (Main Roads Western Australia 2015). The sample is therefore compliant and would not require corrective actions.

As displayed in Figure 4.11 the submitted method specification suggested 10 blows/300 mm is deemed to conservatively correlate to 96% MMDD, and that it is more likely to correlate with 98% MMDD. This method is applicable to all earthworks activities on the project using local black or grey/brown sand as either foundation or backfill.

Figure 4.11: Nicholson Road project – contractor supplied calibration data plot



Method specification recommendations

The contractor recommended that 10 blows/300 mm displacement of the PSP was deemed equivalent to 96% MMDD.

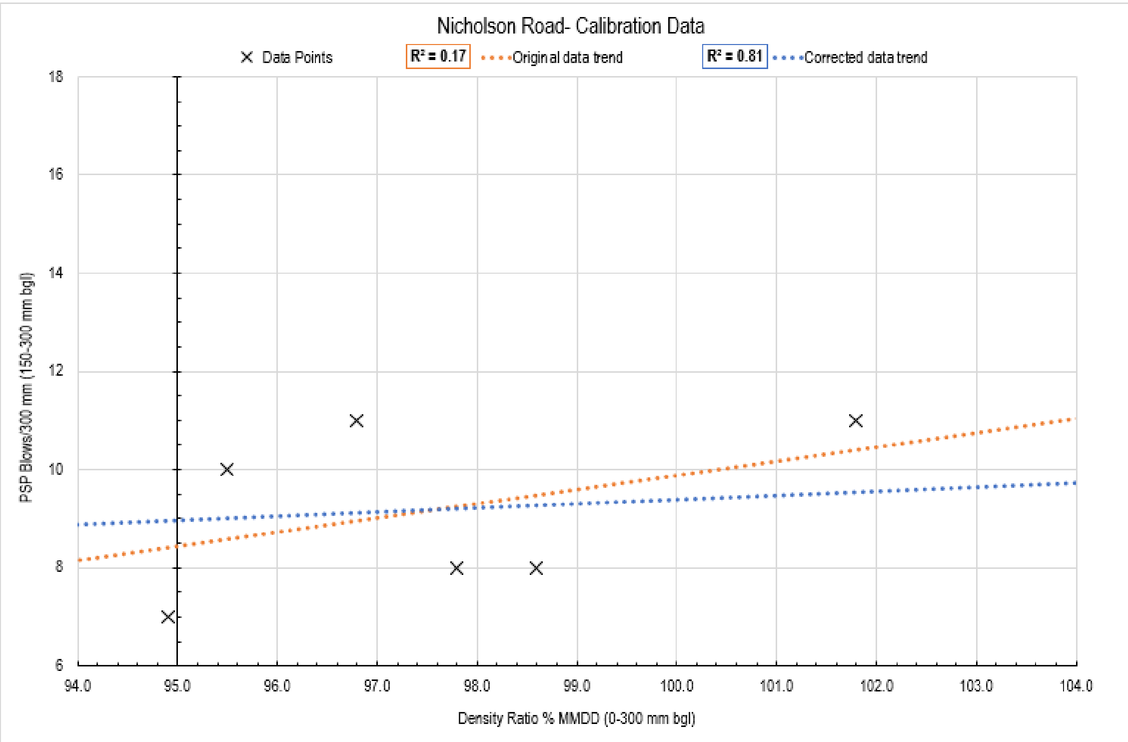
Furthermore, the contractor recommended that in all applications the material (select fill/drainage bedding/embankment fill) properties shall be verified as per MRWA Specification 201 *Quality Systems* (Main Roads Western Australia 2018) at a rate of 1 test per 2500 m^3 in the ground.

NDM testing (WA 324.2), dry density ratio (WA 134.1), MC (WA 110.1), OMC (WA 133.1), PSD (WA 115.2) and PSP testing (AS 1289.6.3.3) shall be undertaken at the initial lift and at a rate of every fifth lot. Additionally, within intermediate lots a test frequency of six PSPs per lot will be completed to ensure consistency of results.

Revised data analysis

The PSP and density data collected by the contractor was subject to an alternative data analysis. Figure 4.12 presents a plot of the number of PSP blows/300 mm for the standard test depth of between 0 mm and 450 mm bgl. Both an uncorrected and corrected trend-line is displayed on the plot, demonstrating the similarity in the trend positions and the difference in R^2 for both trend-lines. Notably, the plot represents only the black sand sourced on site.

Figure 4.12: Nicholson Road project – revised calibration data



Based on this plot, it can be inferred that approximately 9 blows/300 mm will be required to achieve a field density of 95% MMDD.

Issues with contractor-developed method

The method specifications recommended for the Nicholson Road project have the following issues:

- The contractor combined the density results of two types of sand found on site – black sand and grey/brown sand – although the gradings (Table 4.8) indicated that the sands were dissimilar.
- The recommended number of blows/300 mm calculated in the method specification is higher than those inferred from Figure 4.12.

Highlights

Highlights from the Nicholson Road method specification include the following:

- There are ongoing requirements to verify the material properties at a rate of one test per 2,500 m^3.
- The consistency of results is checked with NDM testing (WA 324.2), dry density ratio (WA 134.1), MC (WA 110.1), OMC (WA 133.1), PSD (WA 115.2) and PSP testing (AS 1289.6.3.3) at the initial lift and at a rate of every fifth lot. Within intermediate lots, PSP testing is completed to ensure consistency of results.

4.5.5 Esperance Port

Introduction

A contractor developed a method specification for the use of a PSP as part of the Esperance Port Access Corridor project, to reduce the frequency of NDM testing for field density QA/QC. The document was submitted to Main Roads on 31 May 2013.

The PSP correlation was intended for compaction of embankment construction in roads and MSE walls, to comply with the requirements of MRWA Specification 302 and Specification 201. Calibration was undertaken for Perth sands with a lift thickness of 300 mm.

The density requirements for the bulk earthworks was specified at 95% MMDD.

Material

No PSD test certificates were provided with the submission.

Calibration method

The contractor developed the method specification for two methods of compaction, the roller compaction method and the (diesel platen universell (reversible diesel plate compactor)) DPU compaction method. This included completing parallel PSP and NDM testing. The construction process included the following:

1. Roller compaction method:
   - Water the layer with three passes of the watercart.
   - Place 300 mm of loose sand and compact with ten passes of a vibratory roller.
2. DPU compaction method:
   - Place 150 mm of loose sand and water the layer with one pass of the watercart.
   - Compact with six passes of a (minimum) 300 kg DPU.

- Place an additional 150 mm of loose sand and water the layer with two passes of the watercart.
- Compact with six passes of a (minimum) 300 kg DPU.

3. Conduct PSP testing at six locations.
4. Conduct NDM testing at six randomly-selected locations once Layer 6 has been placed, excavate down 300 mm to the top of Layer 5 and commence NDM testing. Two samples of the material are taken for OMC testing.

The PSP testing was undertaken between a depth of 150 mm and 450 mm bgl with blows/50 mm recorded as per AS 1289.6.3.3. The blow count per 300 mm was then calculated for each test site.

Calibration data

The calibration data supplied by the contractor was submitted in table form. No calibration figure was supplied.

Method specification recommendations

The contractor recommended that 10 blows/300 mm displacement of the PSP are deemed equivalent to correlate with 95% MMDD for the general MSE fill.

Additionally, the contractor states that if technical refusal is achieved, the depth at 20 blows of the PSP is recorded. If less than 10 blows/300 mm displacement is attained, the layer is to be reworked with one pass of a watercart and two passes of a vibratory roller on the top layer, followed by re-testing using the PSP.

It is proposed that, in order to reduce the required testing, PSD and OMC testing be conducted on every fifth layer, in line with the NDM testing.

Revised data analysis

The PSP and density data collected for both the DPU plate compaction and roller compaction methods were subject to an alternative data analysis. Figure 4.13 and Figure 4.14 compares the number of PSP blows/300 mm with the density ratio for the DPU plate compaction method and the roller compaction method, respectively. Both show a corrected and uncorrected trend-line, demonstrating the similarity in the trend positions and the difference in R^2 for both trend-lines.

Based on Figure 4.13, it can be inferred that, to achieve a field density ratio of 95% MMDD, approximately 14 blows/300 mm are required for the DPU plate compaction method. Similarly, Figure 4.14 indicates that, for the roller compaction method, approximately 15 blows/300 mm are required to achieve 95% MMDD.

Figure 4.13: Esperance Port Access Corridor – revised DPU compaction calibration data

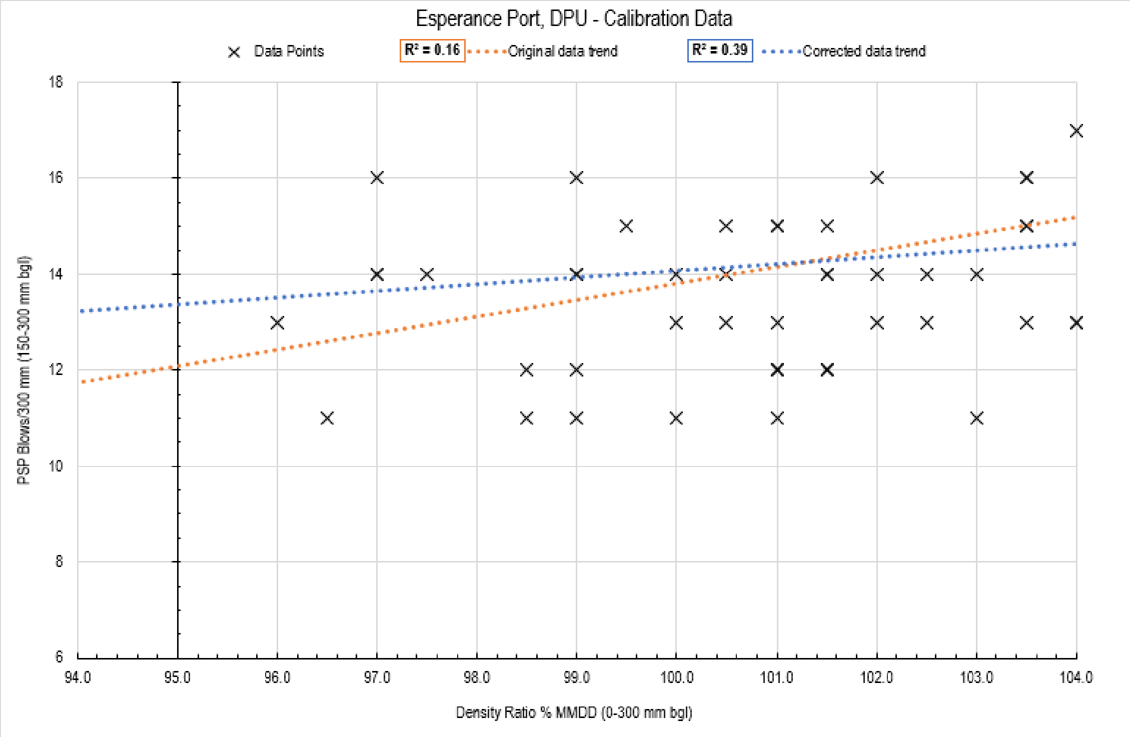
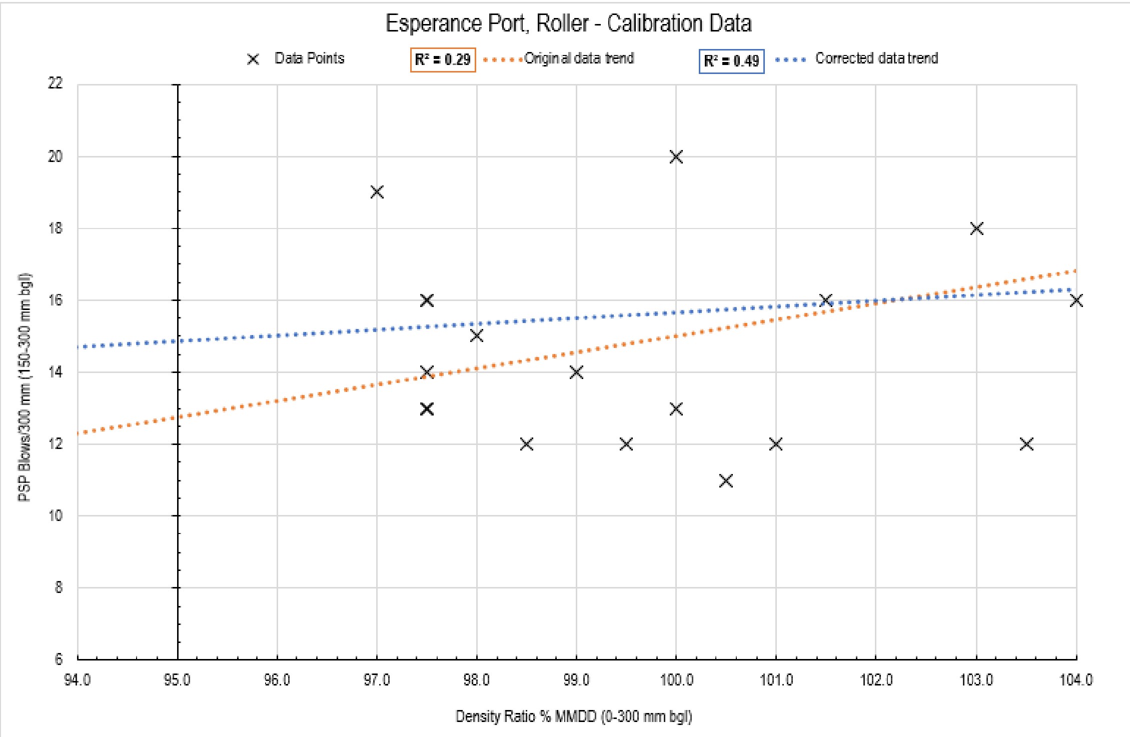


Figure 4.14: Esperance Port Access Corridor – revised roller compaction calibration data



Issues with contractor-developed method

The method specification recommended has the following issues:

- The PSD certificates for the material were not presented.
- The specification not state if the calibration method was a field trial or to be conducted at a separate location.
- The specification did not differentiate between the recommended blows/300 mm for the compaction methods.
- The recommended blows/300 mm calculated in the method specification are much lower than those inferred from Figure 4.13 and Figure 4.14.

Highlights

Notable inclusions for the Esperance Port PSP method specification include:

- There are clear instruction for the calibration for both of the compaction methods that may be employed, including water application and minimum number of compactor passes.
- There are ongoing requirements to verify the material properties using PSD and OMC testing, in accordance with MRWA Specification 201 at every fifth lift.
- Compaction conformance is checked at every fifth layer using NDM testing.

4.5.6 Gateway WA

Introduction

During construction of the Gateway WA project, the contractors of the Gateway Alliance developed two method specifications in which the PSP can be adopted to assist in verifying compaction and minimising the amount of laboratory testing required. The methods were authored by Craig Hugo and are dated 19 May 2014 and 29 August 2014 for 600 mm fill lifts and 300 mm fill lifts, respectively.

The PSP correlations are intended for the construction of embankment fill. Calibration for each method specification was undertaken using several sands:

- method compaction for 300 mm embankment fill lifts:
  - white to grey sand
  - yellow select sand, supplied by Great Sand Supplied
  - sand, supplied by Brajkovich (Brajkovich sand)
- method compaction for 600 mm embankment fill lifts:
  - yellow Perth sand
  - recycled sand, supplied by Capitol
  - Brajkovich sand.

The density requirements for the bulk earthworks was specified at a minimum of 95% MMDD.

Material

No PSD test certificates were provided with the submission.

Calibration method

The construction of a required embankment was used for the calibration trial. A total of three trial lifts, of approximately 500 mm of loose material was prepared using Bassendean sand, totalling 32 NDM and PSP tests. The construction process anticipated for construction of project embankments was mirrored for the calibration trial and included the following:

1. Wet the surface using multiple passes of a water truck.
2. Scarify to a depth of 200 mm using a CAT140H grader.
3. Apply two passes of the 15 t Hamm 3412HT VIO smooth steel drum roller set to high vibration (approx. 50 Hz) with a 1.89 mm vibration amplitude travelling at approximately 5 km/h.
4. Conduct two NDM tests at 300 mm bgl and MC tests in accordance with WA 110.1, WA 134.1, WA 136.1 and WA 324.2.
5. Conduct one PSP test adjacent to each NDM tests in accordance with AS 1289.6.3.3.
6. Repeat steps 3 to 5 until negligible increase in density is observed.

It is important to note that the third trial utilised four passes of the roller at step 3.

The PSP testing was undertaken between a depth of 150 mm and 450 mm bgl with blows/50 mm recorded as per AS 1289.6.3.3. The blow count per 300 mm was then calculated for each test site. NDM testing was undertaken adjacent to the PSP at the standard depth between 0 mm and 300 mm bgl.

Calibration data

The calibration test site data collected by the contractor for the development of the method specification for 300 mm fill lifts is summarised in Table 4.10,Table 4.11 and Table 4.12 for each of the types of sand. The contractor did not provide plots of the calibration data for these three materials. a DCP tip was used in place of the standard PSP tip for the Brajkovich sand due to the silty nature of the sand.

Table 4.10: Gateway WA – 300 mm lift contractor supplied calibration data white to grey sand

Number of passes	Compaction	Site/test location		
		A	B	C
0	PSP blows/300 mm	3	4	3
	Relative density (%)	93	94	92.5
2	PSP blows/300 mm	6	7	6
	Relative density (%)	94.5	99	105
4	PSP blows/300 mm	7	8	8
	Relative density (%)	95	95.5	96
6	PSP blows/300 mm	8	8	9
	Relative density (%)	93.5	95	98.5

Table 4.11: Gateway WA – 300 mm lift contractor supplied calibration data yellow select sand

Number of passes	Compaction	Site/test location					
		1	2	3	4	5	6
8	PSP blows/300 mm	18	16	16	14	12	14

Number of passes	Compaction	Site/test location					
		1	2	3	4	5	6
	Relative density (%)	102.5	97.5	98.2	98.6	100.1	100.2

Table 4.12: Gateway WA – 300 mm lift contractor supplied calibration data Brajkovich sand

Number of passes	Compaction	Site/test location					
		A	B	C	D	E	F
0	DCP blows/300 mm	16	14	13	10	21	16
	Relative density (%)	90.7	91.5	89	88.5	79	84.5
2	DCP blows/300 mm	17	13	18	15	12	15
	Relative density (%)	98.7	97	95	89.5	88	89.5
4	DCP blows/300 mm	14	13	13	19	12	18
	Relative density (%)	94.4	95	91.5	91	85.5	92
6	DCP blows/300 mm	14	18	18	21	23	17
	Relative density (%)	100.2	96.5	92.5	93.5	91	93.5
8	DCP blows/300 mm	16	18	19	17	21	16
	Relative density (%)	96	95	97	91.5	88	91.5

The data collected by the contractor for each of the types of sand used as fill material for the development of the method specification for 600 mm fill lifts is summarised in Table 4.13, Table 4.14 and Table 4.15. However, the contractor did not provide a plot of the calibration data. Similar to the method specification for 300 mm fill lifts, a DCP tip was used in place of the standard PSP tip for the Brajkovich sand.

Table 4.13: Gateway WA – 600 mm lift contractor supplied calibration data yellow Perth sand

Roller passes (no.)	Test	Depth (mm, bgl)	Site 1	Site 2
2	NDM dry density (%)	0–300	92	99
	PSP blows/300 mm – 150–450 mm	150–450	15	17
	NDM dry density (%) at 300 mm	300–600	93.5	98
	PSP blows/300 mm – 300–600 mm	300–600	21	28
4	NDM dry density (%)	0–300	96.5	99
	PSP blows/300 mm – 150–450 mm	150–450	15	18
	NDM dry density (%) at 300 mm	300–600	95	100.5
	PSP blows/300 mm – 300–600 mm	300–600	26	29
6	NDM dry density (%)	0–300	94.5	97
	PSP blows/300 mm – 150–450 mm	150–450	17	14
	NDM dry density (%) at 300 mm	300–600	96.5	102.5
	PSP blows/300 mm – 300–600 mm	300–600	28	26
8	NDM dry density (%)	0–300	98.5	101.5
	PSP blows/300 mm – 150–450 mm	150–450	20	20
	NDM dry density (%) at 300 mm	300–600	101	10.5
	PSP blows/300 mm – 300–600 mm	300–600	28	30

Table 4.14: Gateway WA – 600 mm lift contractor supplied calibration data Capitol recycled sand

Roller passes (no.)	Test	Depth (mm, bgl)	Site 1	Site 2
2	NDM dry density (%)	0–300	90.5	89.5
	PSP blows/300 mm – 150–450 mm	150–450	7	8
	NDM dry density (%) at 300 mm	300–600	96.5	97.5
	PSP blows/300 mm – 300–600 mm	300–600	16	21
4	NDM dry density (%)	0–300	93	94.5
	PSP blows/300 mm – 150–450 mm	150–450	8	10
	NDM dry density (%) at 300 mm	300–600	100	99.5
	PSP blows/300 mm – 300–600 mm	300–600	33	30
6	NDM dry density (%)	0–300	93.5	93.5
	PSP blows/300 mm – 150–450 mm	150–450	10	11
	NDM dry density (%) at 300 mm	300–600	99	98.5
	PSP blows/300 mm – 300–600 mm	300–600	25	21
8	NDM dry density (%)	0–300	94.5	95
	PSP blows/300 mm – 150–450 mm	150–450	11	10
	NDM dry density (%) at 300 mm	300–600	99	98
	PSP blows/300 mm – 300–600 mm	300–600	21	22

Table 4.15: Gateway WA – 600 mm lift contractor supplied calibration data Brajkovich sand

Roller passes (no.)	Test	Depth (mm, bgl)	Site 1	Site 2	Site 3	Site 4	Site 5	Site 6
2	NDM dry density (%)	0–300	91.8	97.5	96	94.5	98.5	97
	DCP blows/300 mm – 150–450 mm	150–450	12	12	10	11	10	12
	NDM dry density (%) at 300 mm	300–600	89	90	96	93.5	93.5	98
	DCP blows/300 mm – 300–600 mm	300–600	28	36	34	34	38	39
4	NDM dry density (%)	0–300	96.9	94.5	98.5	97.5	98	98
	DCP blows/300 mm – 150–450 mm	150–450	16	12	13	14	14	12
	NDM dry density (%) at 300 mm	300–600	93.7	97.5	92	97	95	100
	DCP blows/300 mm – 300–600 mm	300–600	36	35	36	35	36	39
6	NDM dry density (%)	0–300	101.5	101	99.5	101.5	98.5	99
	DCP blows/300 mm – 150–450 mm	150–450	18	12	18	17	15	15
	NDM dry density (%) at 300 mm	300–600	97.5	100	104	95	96.5	96.5
	DCP blows/300 mm – 300–600 mm	300–600	40	39	43	39	41	38

Method specification recommendations

The PSP blows relative to the target relative compaction for each of the sand types used in the method specification for 300 mm embankment fill lifts is summarised in Table 4.16. Additionally, the contractor stated that blows per compacted layer in a 300 mm lift must be achieved with the following:

- The full thickness of the lift must be conditioned to its OMC.
- A recommended minimum of eight passes with a roller or six passes with a hand compactor is adopted or as required to achieve the specified compaction.

- The PSP/DCP penetration values apply only to the material and specified relative compactions presented in Table 4.16.
- Where changes occur to the material type, standard lifts of 300 mm must recommence with compaction testing carried out in accordance with the specification until a suitable correlation is established.
- NDM testing must be carried out at a minimum of every third lift, i.e. every 900 mm, and it should be confirmed on site that the correlation provided is still relevant.
- If testing through multiple layers the overlying layer must be removed prior to commencing PSP test, i.e. can only penetrate one 300 mm lift at a time.
- PSP testing must be carried out at the same frequency per lot as required when using the NDM or as agreed with the quality team.

Table 4.16: Gateway WA – 300 mm lift method specification contractor recommended PSP blows/300 mm

Material	Target relative compaction (% MMDD)	PSP blows/300 mm	DCP blows/300 mm
White to grey sand	95	8	–
Great Sand Supplies select yellow sand(1)	95(1)	14(1)	–
Brajkovich sand(2)	95(2)	–	20

1 Please note that to achieve these results on site the material behavior is such that it requires placement of the following layer to confine it. Therefore, it is recommended that conformance NDM tests and PSPs be carried out on underlying layers after the overlying layer is placed and compacted.

2 It is recognized that the Brajkovich sand source can vary in its silt/clay content. It is therefore the responsibility of the person/s using these correlations to ensure recalibration is undertaken each time there is significant variation in the material or wherever NDM testing has been carried out, i.e. every third layer as a minimum.

Table 4.17 summarises the number of PSP blows required to achieve the target relative compaction for each of the sand types used in the method specification for 600 mm embankment fill lifts. The blows per layer must be achieved with the following limitations/guidelines:

- The full thickness of the lift must be conditioned to its OMC.
- A recommended minimum of eight passes with a smooth drum roller.
- The PSP/DCP penetration values apply only to the material and the target relative compactions presented Table 4.17.
- Where changes occur to the material type, standard lifts of 300 mm must recommence with compaction testing carried out in accordance with the specification until a suitable correlation is established.
- NDM testing must be carried out at the surface and 300 mm below the surface of the 600 mm lift on every third 600 mm lift.
- PSP testing must be carried out at the same frequency per lot as required for the NDM.

Table 4.17: Gateway WA – 600 mm lift method specification contractor recommended PSP blows/300 mm

Material	Target relative compaction (% MMDD)	PSP blows (150–450 mm)	PSP blows (300–600 mm)	DCP blows (150–450 mm)	DCP blows (300–600 mm)
Yellow Perth sand	95	12	24	–	–
Capitol recycled sand	95	12	20	–	–
Brajkovich sand(1)	95	–	–	15	40

1 It is recognized that the Brajkovich sand source can vary in its silt/clay content. It is therefore the responsibility of the person/s using these correlations to ensure recalibration is undertaken each time there is significant variation in the material or wherever NDM testing has been carried out, i.e. every third layer as a minimum.

Revised data analysis – 300 mm lifts

The PSP and density data collected for all sands for both the 300 mm and 600 mm method specifications was subject to an alternative data analysis.

The number of PSP/DCP blows/300 mm for the 300 mm lift method are compared with the density ratio for each of the three materials in Figure 4.15, Figure 4.16 and Figure 4.17. This shows a corrected and uncorrected trend-line, demonstrating the similarity in trend positions and the difference in R^2 for both trend-lines.

Figure 4.15: Gateway WA – revised 300 mm lift calibration data white-grey sand

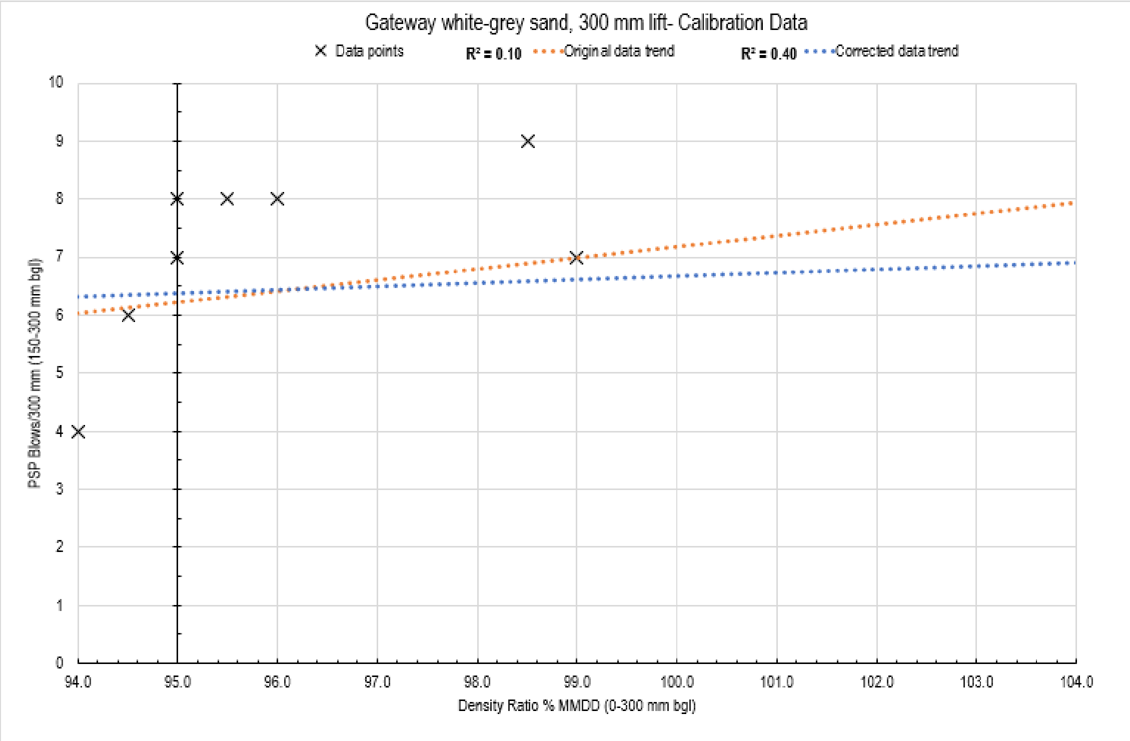


Figure 4.16: Gateway WA – revised 300 mm lift calibration data select yellow sand

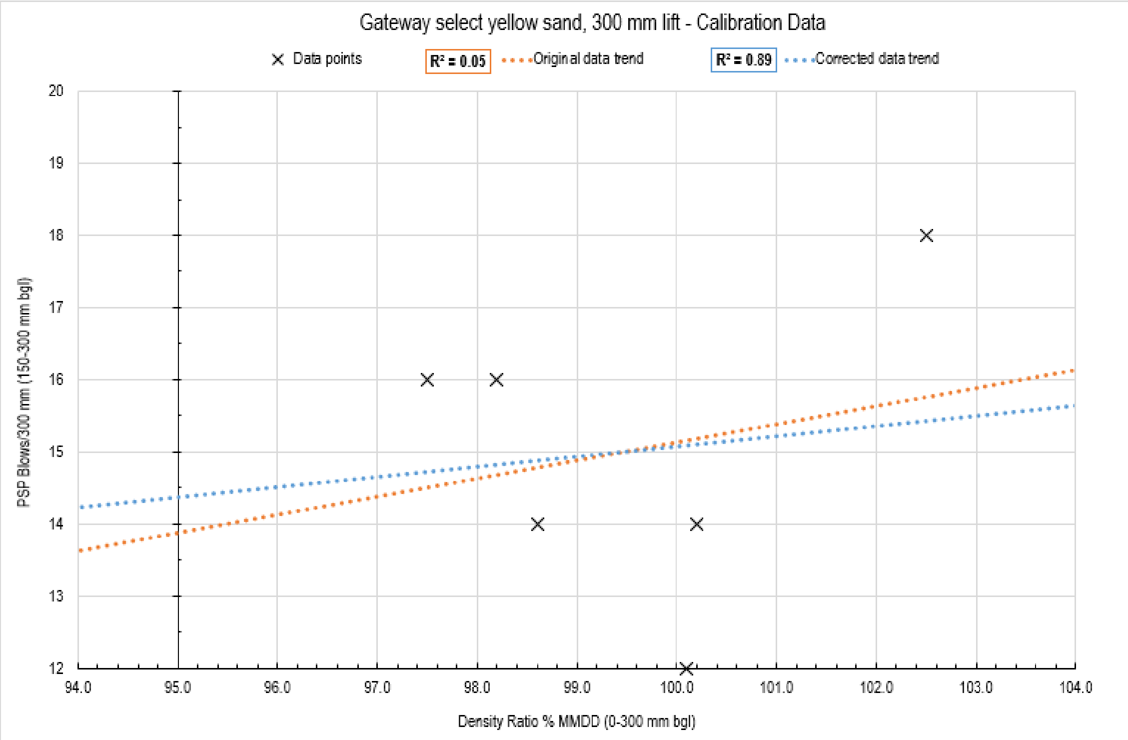
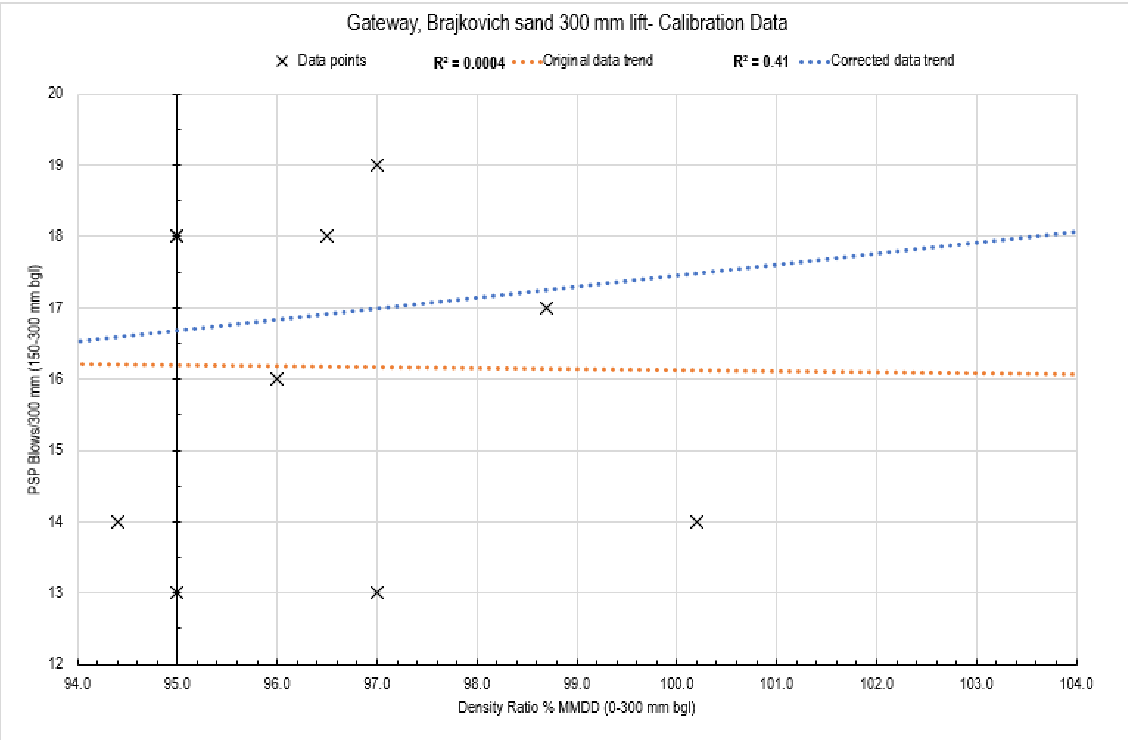


Figure 4.17: Gateway WA – revised 300 mm lift calibration data Brajkovich sand



Based on these plots, the revised recommended blows/300 mm are presented in Table 4.18.

Table 4.18: Gateway WA – 300 mm lift revised PSP blows/300 mm

Material	Target relative compaction (% MMDD)	Revised analysis	
		PSP blows/300 mm	DCP blows/300 mm
White to grey sand	95	7	–
Great Sand Supplies select yellow sand	95	15	–
Brajkovich sand	95	–	17

Revised data analysis – 600 mm lifts

The number of PSP/DCP blows/300 mm for the 600 mm lift method are compared with the density ratio between 150 – 450 mm and 300 – 600 mm are shown in Figure 4.18, Figure 4.19 and Figure 4.20 respectively. This shows a corrected and uncorrected trend-line, demonstrating the similarity in trend positions and the difference in R^2 for both trend-lines.

Figure 4.18: Gateway WA – revised 600 mm lift calibration data yellow Perth

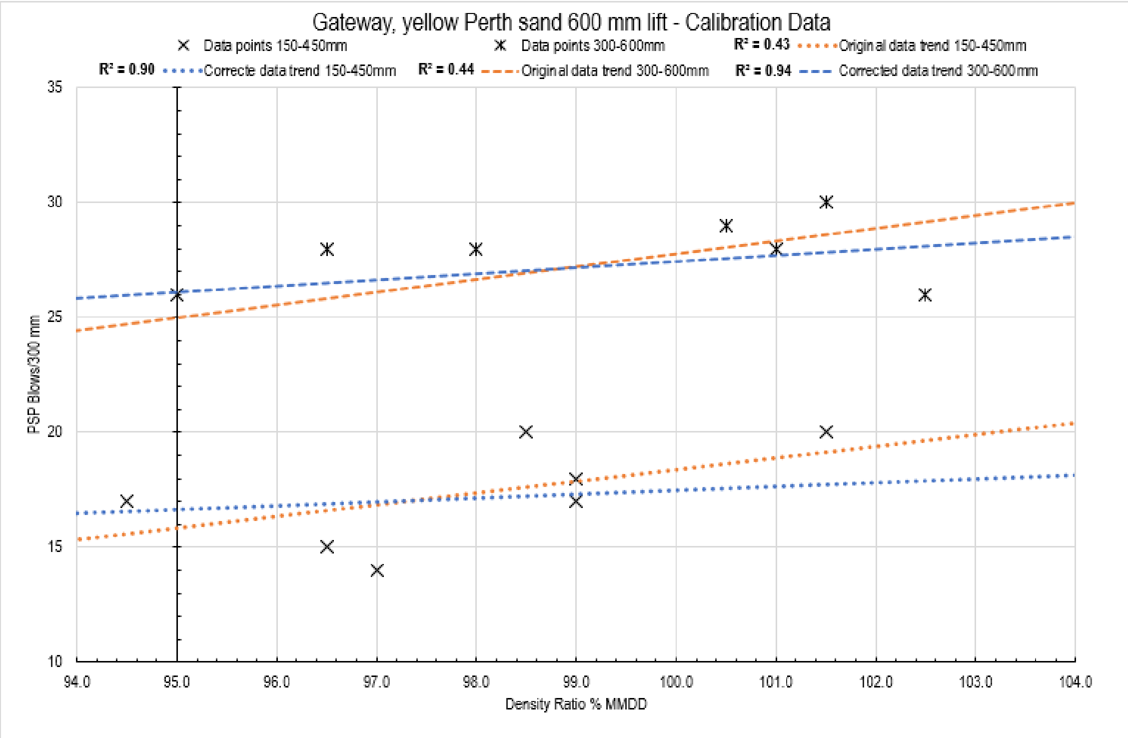


Figure 4.19: Gateway WA – revised 600 mm lift calibration data Capitol recycled sand

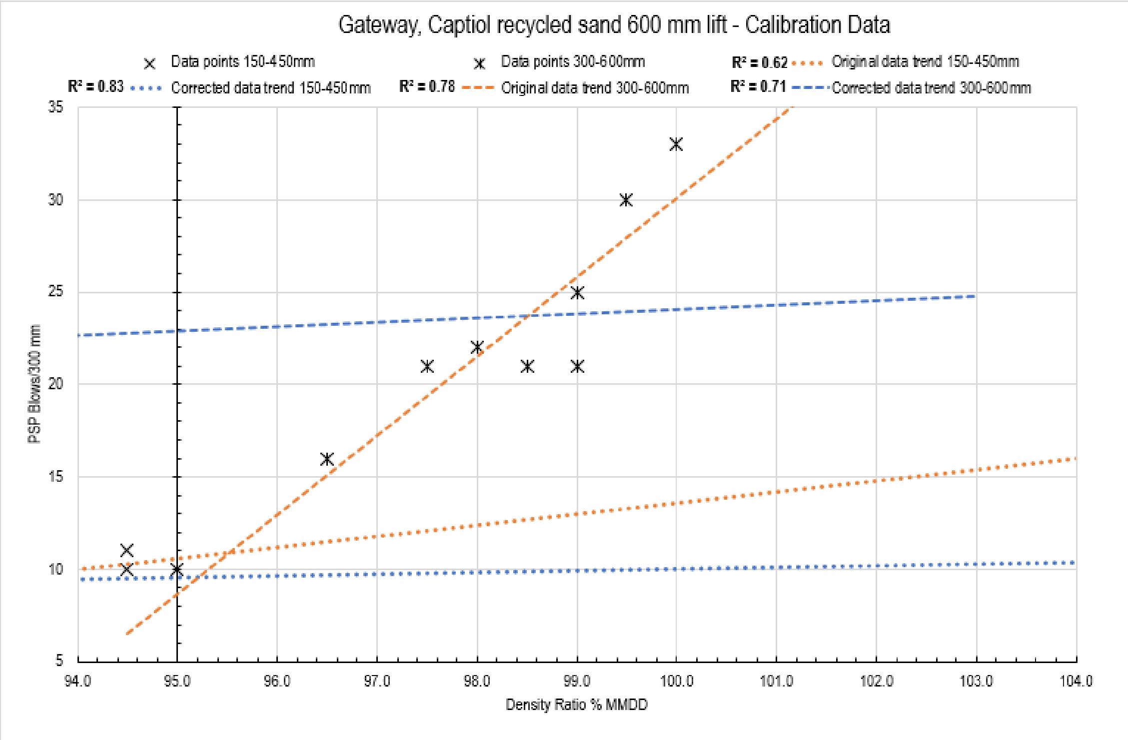
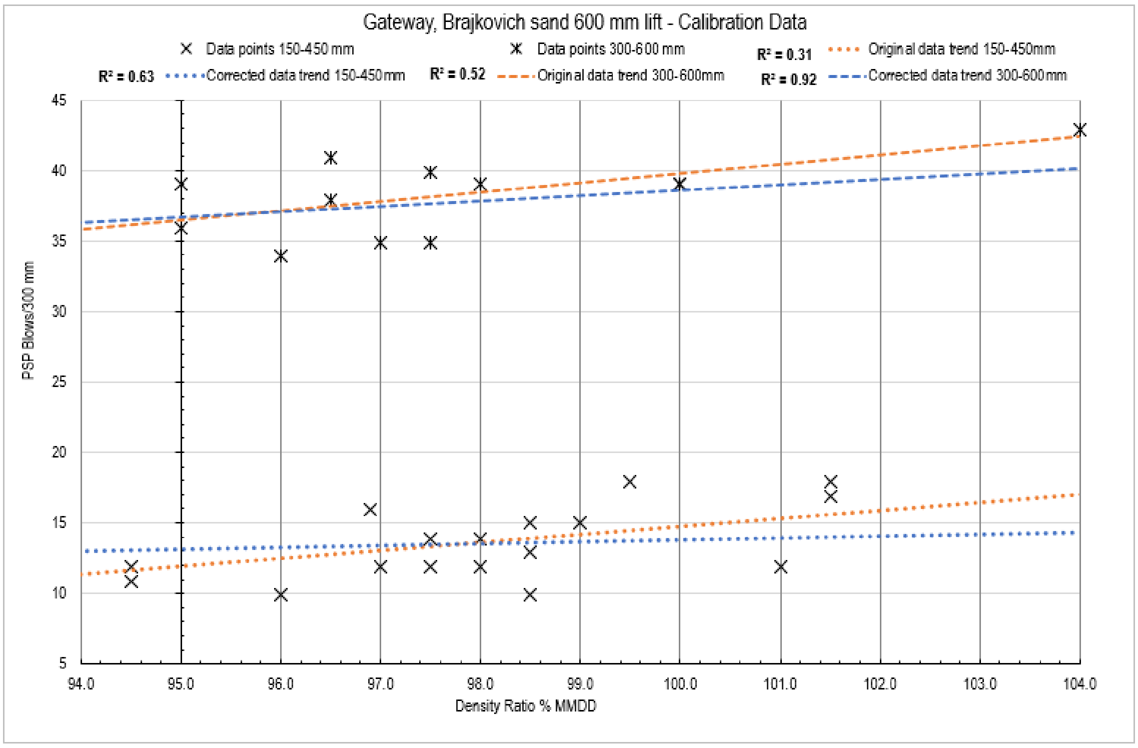


Figure 4.20: Gateway WA – revised 600 mm lift calibration data Brajkovich sand



It is important to note that although shows that the corrected Capitol recycled sand R^2 value for 300 – 600 mm is less than the R^2 obtained with the original data, the corrected number of blows/300 mm is closer to what was recommended by the contractor (20 blows/300 mm). This indicates that a number of outliers may have been removed from the dataset to obtain the contractor recommended number of blows/300 mm.

Based on these plots, the revised recommended blows/300 mm are presented in Table 4.19.

Table 4.19: Gateway WA – 600 mm lift revised PSP blows/300 mm

Material	Target relative compaction (% MMDD)	PSP blows (150–450 mm)	PSP blows (300–600 mm)	DCP blows (150–450 mm)	DCP blows (300–600 mm)
Yellow Perth sand	95	17	27	–	–
Capitol recycled sand	95	10	23	–	–
Brajkovich sand	95	–	–	14	37

Issues with contractor-developed method

The method specifications recommended for the Gateway WA project have the following issues:

- PSD certificates for each material type are not presented.
- The recommended PSP/DCP blows calculated in the method specification are generally different to those inferred from the revised analysis.

Highlights

Notable inclusions for the Gateway WA method specification include:

- There is a different number of required PSP/DCP blows determined for each of the types of sand and lift thicknesses.
- There are clear instructions for the construction process, including passes of the water truck, scarification as well as the roller passes, vibration and speed.
- Separate relationships between blows and relative compaction were developed for the 300 mm and 600 mm lift thicknesses.
- Changes in material type require a new correlation between NDM and PSP.
- Compaction conformance is checked at every third layer using NDM testing.

4.6 Summary and Recommendations

The purpose of the literature review and analysis of PSP usage was to develop guidance to enable contractors or MRWA to develop project-specific PSP method specifications.

The contents and outcome of each of the case studies are summarised in Appendix C, including a summary of highlights and issues of each case study.

General findings from the review and analysis of the PSP include:

- The PSP is typically only used on two types of materials – Perth sands and select fill material – and in accordance with MRWA Specification 302.
- Tests must be conducted on each type of soil due to the variable nature of the material to ensure uniformity for PSP blow counts to be accepted as useful guides to design or control.
- Sand type has the most significant impact on the PSP count, whereas the effect of moisture content, apart from saturated, submerged or completely dry, was minimal.

- There is no universal relationship between blow counts and depth for any given relative density. It is suggested that the use of the PSP to investigate the degree of compaction for depths other than the standard depth of between 150 mm and 450 mm interval specified in AS 1289.6.3.3 is unreliable without site-specific calibration.
- The statistical correlation between blows/300 mm and in situ density is often weak. Therefore it is important to note that the analysis only establishes a likely minimum for density confirmation.
- Method specification submissions vary and often do not include the necessary information required for a complete calibration. Inconsistencies in the data provided by contractors also made method specification comparisons difficult.

The findings of the literature review and analysis of PSP usage indicate that the development of a framework outlining the requirements of a method specification may present a low-risk approach for PSP implementation as a QC tool. It is recommended that the proposed framework is trialled in future construction projects to determine its suitability and applicability for practical use and to determine whether or not it improves the quality of the PSP method specification submissions.

4.7 Recommended Framework Requirements

The following sections draw on the issues and highlights of the case studies presented in Section 4.5 and Section 4.6 to develop the recommended contents and requirements of all future submitted PSP method specifications. Generally, the proposed framework was developed to cover the highlights whilst minimising the issues of the reviewed method specifications. This proposed framework includes the project background and applicability, construction details, material characteristic requirements, calibration, trial data, data summary and the ongoing monitoring and re-calibrations

A summary checklist of the requirements for use by the contractor when developing a submission is included in Appendix C.

4.7.1 Project Background and Applicability of Method Specification

The method specification shall be developed on a project-by-project basis to assist in verifying compaction and minimising the amount of laboratory testing required. Furthermore, the method specification shall state its purpose and a summary of the material description, source, lift thickness, intended application (i.e. subgrade or select fill for embankments) and density compliance requirements.

4.7.2 Proposed Construction Method

The method specification developed by the contractor shall detail the following:

- project dimensions, area of project and volume of material
- material placement and water addition/mixing methodology
- maximum loose lift thicknesses for compaction
- compaction plant details (i.e. number and type or compaction rollers viz. drum type, static mass, vibratory capacity, compactive effort, machine manufacturer and model identification)
- proposed compaction sequence utilising identified compaction plant.

4.7.3 Material Characterisation Requirements

The material anticipated to be used shall be characterised in accordance with MRWA Specification 302 *Earthworks* (Main Roads Western Australia 2015). Unless otherwise specified or approved by the Superintendent, material intended for use as select fill shall be non-cohesive granular material complying with the PSD of MRWA Specification 302, Table 302.01 (Table 4.2). Material for embankments or subgrades that are deemed to be Perth sands shall comply with the PSD of MRWA Specification 302, Table 302B.1 (Table 4.1).

Characterisation of the material shall be conducted by testing the PSD (WA 115.2), MC (WA 110.1) and OMC (WA 133.1). At least two samples shall be tested for each method. Test certificates shall be included with the method specification submission.

4.7.4 Calibration

Option 1: Trial Calibration

The development of a method specification for placement of material shall be conducted first by undertaking a compaction trial at a location separate from works. The construction method during the compaction trial shall be the same as the previously described construction method. The following information shall be recorded and provided to MRWA by the contractor:

- location, date, area of trial and layout figure
- equipment detail (i.e. plant models, water conditioning, vibration frequency, roller speed and compaction pattern)
- lift preparation and sequence (should match the anticipated construction method), sampling locations (i.e. staggered)
- type of calibration (i.e. fixed roller passes followed by density testing of each lift, or testing after each pass for one lift)
- details of the PSP, NDM, PSD, MDD/OMC and MC testing amounts and sequence (i.e. six PSP tests per lift, two NDM tests per lift, etc.)
- testing of the PSP is in accordance with AS 1289.6.3.3.

Option 2: Field Calibration

Alternatively, calibration may be undertaken in the field as part of the works using the same steps as outlined in Option 1: Trial Calibration.

4.7.5 Calibration Data

The data presented in the method specification report shall include the NDM and PSP results relating to differing soil types. This shall be presented in tabular form allowing the comparison of PSP blows/300 mm to the MMDD measured using the NDM.

These results shall be represented in graphical form showing the density ratio on the x-axis and PSP blows/300 mm on the y-axis. A linear trend line (with regression coefficient) with a y-axis intercept of 1.0 is used to determine the minimum number of blows required to achieve the specified density.

For method specifications that include the use of the PSP to investigate the degree of compaction for depths other than the standard, between 150 mm and 450 mm depth interval specified in AS 1289.6.3.3, the data shall be presented separately, where each alternative depth shall have its own linear trend line (with regression coefficient) to determine the required minimum number of PSP blows/300 mm required to achieve the specified density.

The conformance of the dataset shall be determined using the characteristic density method outlined in ERN8 (Main Roads Western Australia 2008). Test certificates of all tests conducted relevant to the development of the method specification shall be provided.

4.7.6 Summary of Calibration

Based on the data presented in the report, the contractor shall present a summary of the PSP blows/300 mm required to achieve the target compaction per layer for each material type used on the project. Any notable limitations and/or guidelines that shall be followed for construction shall be listed (i.e. minimum number of roller passes, depth applicability of PSP penetration values).

4.7.7 Ongoing Monitoring and Re-calibration

The minimum testing frequency to determine the conformance of ongoing work processes with specified characteristics shall be in accordance with MRWA Specification 201 with the exception of NDM and PSP testing unless specified otherwise by MRWA personnel, as follows:

Table 4.20: Required testing and frequencies

Test	Test method	Frequency	Comments
Field density testing			
PSP testing	AS 1289.6.3.3	6 per lot	▪ Randomly located ▪ Must conform to the previously determines blow/300 mm requirements ▪ All testing is to be completed before placement of the next lift ▪ In the event a lot fails when tested by PSP, that lot shall be re-worked and re-tested by NDM. The next three consecutive lots shall then be testing using the NDM and if these are found to be compliant, the method specification process may resume.
Ongoing conformance testing			
PSD	WA 115.2	2 per lot	▪ All testing is to be completed before placement of the next lift. ▪ If changes to material occur, compaction testing must be carried out in accordance with the Specification 201 until a suitable, revised correlation between the NDM and PSP is established.
Dry density ratio/ NDM	WA 134.1 and WA 342.2	Every 5th lot	▪ All testing is to be completed before placement of the next lift. ▪ In the event a lot fails when tested by NDM, that lot shall be re-worked and re-tested by NDM. The next three consecutive lots shall then be testing using the NDM and if these are found to be compliant, the method specification process may resume.
Construction characteristic MC	WA 110.1 or WA 110.2	1 per lot	▪ All testing is to be completed before placement of the next lift.
OMC	WA 133.1 or WA 133.2	2 per lot	▪ All testing is to be completed before placement of the next lift.

5 SPECIFICATION OF MAXIMUM AND MINIMUM DENSITY FOR SANDS

5.1 Introduction

During construction, field measurements of the in situ material are performed to determine the field dry density of the soil, which is typically required to be a percentage of the MDD obtained in laboratory testing. Achieving high density in the soil implies low voids, high particle interlock and low moisture sensitivity. However, obtaining repeatable laboratory MDD results for cohesionless sands, which are typically used in subgrade and embankment fill applications in WA, can be difficult. Therefore, the specification of a density index may be considered as an alternative for the laboratory MDD test for cohesionless sands into compliance guidance and documentation.

5.2 Index Density (Relative Density)

Australian and international standards exist for the determination of maximum and minimum index densities. Notably, the American Society for Testing Materials (ASTM) methods refer to the value as index density or relative density whereas the Australian Standards refer to the figure as density index. The maximum and minimum index densities may be determined in accordance with the following standards:

- ASTM D4253: *Standard test methods for maximum index density and unit weight of soils using a vibratory table*.
- ASTM D4254: *Standard test methods for minimum index density and unit weight of soils and calculation of relative density*.
- AS 1289.5.5.1: *Methods of testing soils for engineering purposes: soil compaction and density tests – determination of the minimum and maximum dry density of a cohesionless material – standard method.*
- AS 1289.5.6.1: *Methods of testing soils for engineering purposes: soil compaction and density tests – compaction control test – density index method for a cohesionless material.*

5.2.1 ASTM Methods

Maximum Index Density

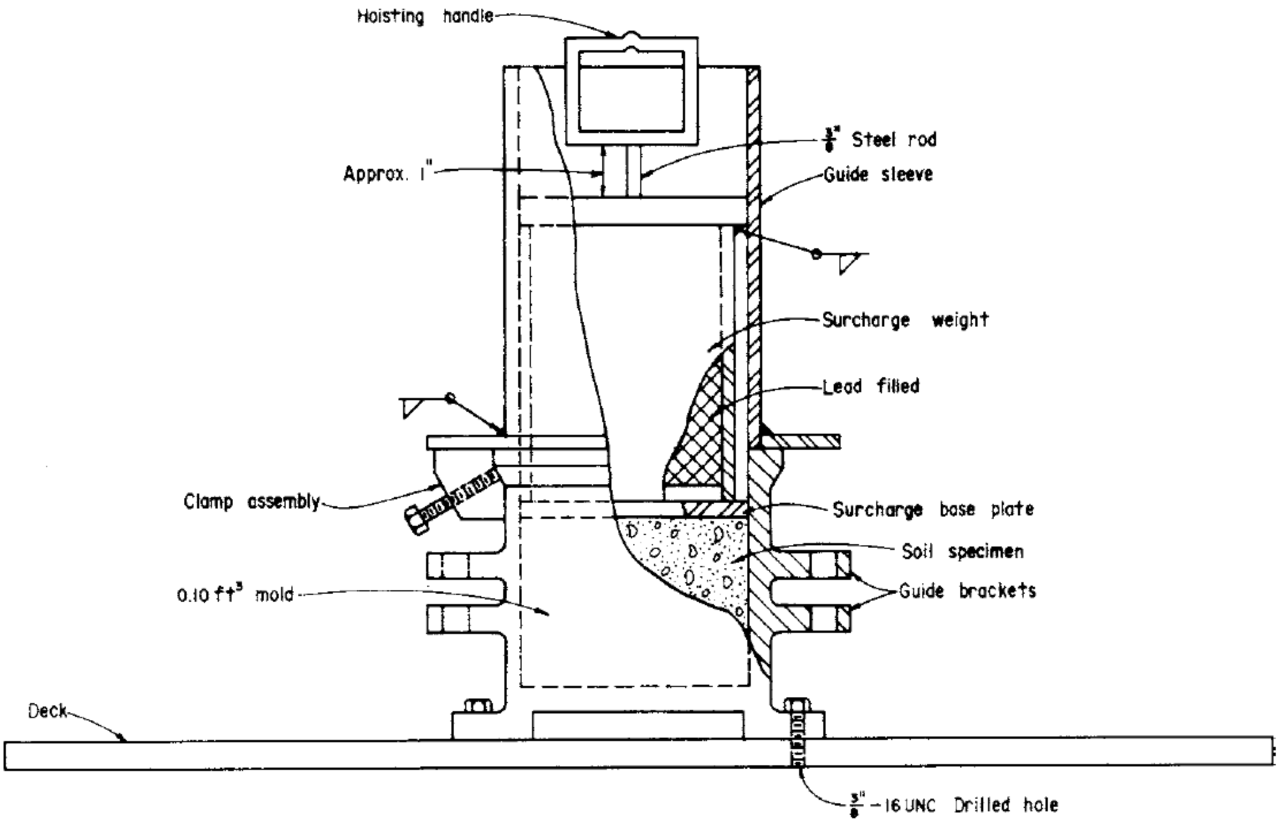
Maximum index density is the densest state of compaction for a cohesionless soil that can be attained using a standard laboratory compaction procedure, minimising particle segregation and breakdown. In accordance with ASTM D4253 the maximum index density can be determined using four alternative methods, typically depending on available equipment as follows:

- Method 1A – oven-dried soil and an electromagnetic, vertically vibrating table
- Method 1B – wet soil and an electromagnetic, vertically vibrating table
- Method 2A – oven-dried soil and an eccentric or cam-driven, vertically vibrating table
- Method 2B – wet soil and an eccentric or cam-driven, vertically vibrating table.

ASTM D4253 recommends that both the wet and dry methods are performed when beginning a new job or encountering a new soil type as the wet method may yield significantly higher values for some soils.

The dry methods (Method 1A and 2A) are carried out by filling a mould (Figure 5.1) with oven-dried soil, placing a surcharge base plate to the surface of the soil and attaching the mould to the vibrating table. Whether vibration is electromagnetic or eccentric or cam-driven is determined by the availability of equipment.

Figure 5.1: Schematic drawing of a typical mould assembly



Source: ASTM D4253.

Dial indictor gauge readings are obtained on opposite sides of the surcharge base plate and the density is then calculated by measuring the mass of the soil filling the mould and subtracting the mass of the empty mould in accordance with Equation 10. The test should be conducted on the soil until consistent values (preferably within 2%) are obtained.

$$\rho_{dmax,n} = \frac{M_s}{V} \qquad 10$$

where

$\rho_{dmax,n}$	=	maximum index density for given trial (mg/m^3)
M_s	=	mass of the tested dry soil (mg)
V	=	volume of the tested dry soil (mg) $V = V_c - A_c * H * CF$
V_c	=	calibrated volume of mould (m^3)
A_c	=	calibrated cross-sectional area of mould (m^2)
H	=	positive difference in elevation between top surfaces of mould and tested soil (bottom surface of surcharge base plate) (m)

$$H = (R_f - R_i + T_p)\ for\ clockwise\ reading\ dial\ indicator$$
$$H = (R_i - R_f + T_p)\ for\ anti-clockwise\ reading\ dial\ indicator$$

R_i = initial dial reading (mm)

R_f = average of final dial gauge readings on opposite sides of the surcharge base plate after completion of the vibration period (mm)

T_p = thickness of surcharge base plate (mm)

CF = conversion factor (0.001 for dial reading units in mm and volume requirements in m^3)

The wet methods (Method 1B and 2B) are conducted on either oven-dried soil to which sufficient water is added or, wet soil from the field. In the wet method, the mould is attached to the vibrating table and turned on, where wet soil is slowly added to fill the mould. The surcharge base plate is then attached, and the assembly is vibrated. Dial indicator-gauge readings are taken and the wet soil is then removed and oven-dried. Similar to the dry method, the index density is then calculated using Equation 10 and tests are conducted until consistent values are obtained.

Minimum Index Density

The minimum index density represents the loosest condition of cohesionless, free-draining soil that can be attained by a standard laboratory procedure, which prevents bulking and minimises particle segregation. In accordance with ASTM D4254 the minimum index density can be determined using three alternative methods, typically depending on available equipment as follows:

- Method A – using a funnel pouring device or a hand scoop to place material in mould
- Method B – depositing material into a mould by extracting a soil filled tube
- Method C – depositing material by inverting a graduated cylinder.

It is noted that ASTM D4254 states that Method A is preferred and that Method B and Method C are typically used in conjunction with special studies, especially where there is not enough material to fill the mould required by Method A.

In Method A, the minimum index density is determined by pouring oven-dried soil into the mould, maintaining a free fall height of approximately 13 mm until the material is above the top of the mould. The excess material is then trimmed using a straight edge and the Equation 11. Method B is determined similarly except that a thin-walled tube is placed inside the mould into which the soil is poured and the tube removed once the mould is filled. Method C involves placing soil into a graduated cylinder, tipping the cylinder upside down and quickly back to its original position. The minimum index density of both Method B and Method C are also calculated using Equation 11.

$$\rho_{dmin,n} = \frac{M_s}{V} \qquad (11)$$

where

$\rho_{dmin,n}$ = minimum index density for given trial (mg/m^3)

M_s = mass of the tested dry soil (mg)

V = volume of the tested dry soil (m^3)

Relative Density

Once the maximum and minimum index densities have been determined the relative density, expressed as a percentage of the difference between the maximum and minimum index densities of the soil is calculated using Equation 12.

$$D_d = \frac{\rho_{dmax} * (\rho_d - \rho_{dmin})}{\rho_d * (\rho_{dmax} - \rho_{dmin})} * 100 \quad (12)$$

where

D_d	=	relative density (%)
ρ_d	=	dry density of a soil deposit or fill at the given void ratio (mg/m^3)
ρ_{dmax}	=	maximum index density (mg/m^3)
ρ_{dmin}	=	minimum index density (mg/m^3)

5.2.2 Australian Standards

Maximum Density Index

The method for determining the maximum density index of cohesionless soils is described in AS 1289.5.5.1. The procedure and apparatus outlined are in accordance with ASTM D4253 Method 1B, there is no mention of using oven-dried soil to fill the mould (Method 1A) or the cam-driven vertically vibrating table (Methods 2A and 2B). However, the MDD is determined using Equation 13.

$$\rho_d = \frac{m_s * 1000}{V} \quad (13)$$

where

ρ_d	=	maximum/minimum dry density (tonnes/m^3)
m_s	=	mass of dry material in mould (kg)
V	=	volume of mould (cm^3)

AS 1289.5.5.1 also notes that the method is appropriate for soils containing up to 5% by mass, soil particles passing the 0.075 mm sieve, except that silty sands with non-plastic fines may contain up to 12% passing the 0.075 mm sieve. Furthermore, to obtain a more precise measurement of maximum density, the relationship between the density and the double amplitude of vertical vibration should be found.

Minimum Density Index

The minimum density index is determined in accordance with AS 1289.5.5.1. Notably, the method and apparatus are in accordance with ASTM D4254 Method A. The minimum dry density is calculated using Equation 13.

Density Index

The density index of a cohesionless material is calculated using the field dry density of a soil, as well as the laboratory maximum and minimum dry densities in accordance with Equation 14.

$$I_D = \frac{\rho_{dmax} * (\rho_d - \rho_{dmin})}{\rho_d * (\rho_{dmax} - \rho_{dmin})} * 100 \quad (14)$$

where

I_D	=	density index (%)
ρ_d	=	field dry density of a soil (tonnes/m^3)
ρ_{dmax}	=	maximum dry density t/m^3)
ρ_{dmin}	=	minimum dry density (t/m^3)

5.3 Australian Road Agency Specifications

Typically, the in situ density of compacted materials for each of the reviewed road agencies is determined in accordance with the test methods summarised in Table 2.1. Alternative methods of determining the in situ density of cohesionless soils for the reviewed road agencies are summarised in Table 5.1, if specified.

Table 5.1: Summary of current compaction compliance test for cohesionless sands

Road Authority	Specification	Allowed test	Test comments	Standard test procedure
Department of Transport and Maine Roads, QLD	MRTS04 *General Earthworks* (TMR 2018a)	Density index	To be used where laboratory MMDD test gives meaningless answers.	AS 1289.5.5.1 and AS 1289.5.6.1
Roads and Maritime Services, NSW/ACT	R44 *Earthworks* (RMS 2012)	Density in situ of road construction materials (fixed volume extractive method)	Determining field density and relative compaction of fine to medium grained cohesionless materials.	RMS Test Method T165 (RMS 2012)

This indicates that TMR is the only jurisdiction that specifies that the density index method shall be used for density compliance of compacted cohesionless sands.

5.3.1 TMR Density Index

TMR’s approach to specifying compaction density compliance for cohesionless materials has involved the use of the density index for approximately 30 years. However, prior to the 2013 update of MRTS04, the density index was determined using TMR-developed test methods for density index, Q132A and Q132B. In the 2013 update of MRTS04, the TMR test methods were replaced with AS 1289.5.5.1 and AS 1289.5.6.1. Table 5.2 summarises the density compliance tests required by TMR for each material used in general earthworks, and Table 5.3 outlines the density requirements.

In personal correspondence on 12 December 2018, Brian Lowe (Senior Manager Road Materials, TMR) stated that the embankment material and select fill requirements specified by TMR will generally rule out of the use of sands due to plasticity index and linear shrinkage requirements, respectively. Furthermore, it was noted that, when used, the requirement for a minimum density index of 70% will usually be met by wetting the sand and applying light compaction. Additionally, it was stated that preferred method for in situ density testing is the sand replacement test rather than the NDM due to historical difficulties with the NDM.

Table 5.2: TMR required method for determination of density

Material category	Compaction method	Density compliance tests
Cohesionless sands	Compacted layer method	Density index
Soils other than above which, after compaction, have less than 35% stone retained on the 37.5 mm sieve	Compacted layer method	Relative compaction
Coarse grained soils with more than 35% of stone retained on the 37.5 mm sieve	Mechanical interlock method	Nil on material in general

Adapted from TMR (2018c).

Table 5.3: TMR density requirements

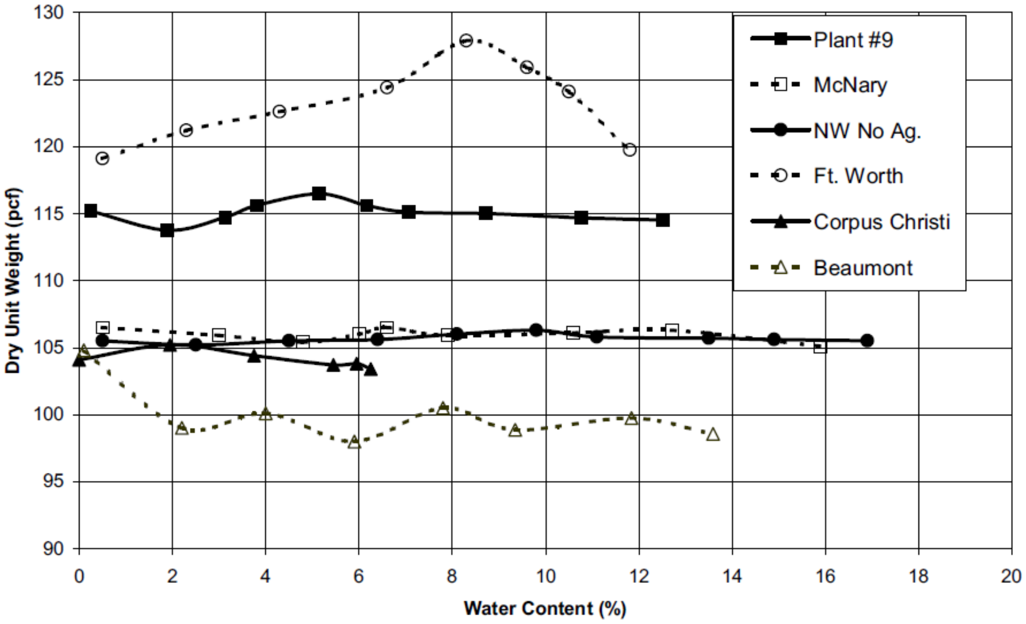
Application	Material	Compaction standard(1)	
		Minimum(2)	Maximum(3)
Embankment fill (including subgrade)			
Top 300 mm below subgrade level	Class A1 or B	97%	–
	Unbound granular or stabilised material		–
	Cohesionless[4]	70% density index	–
Greater than 300 mm below subgrade level	Class A1, A2 or B	95%	–
	Unbound granular or stabilised material		–
	Class C or D (low or medium rainfall zone)		–
	Class C or D (high rainfall zone)	90%	96%
	Cohesionless[4]	70% density index	–
Other			
Backfill	Cohesive	95%	–
	Cohesionless(4)	70% density index	–
Non trafficked trench areas and ground surface treatment	Cohesive	90%	–

1 The compaction standard shall be relative compaction except for cohesionless material where density index shall be used.
2 Lower characteristic value unless otherwise required.
3 Upper characteristic value unless otherwise required.
4 Where 10 mm or 20 mm nominal size bedding material is used density index testing is not required.
Source: TMR (2018c).

5.4 Literature Review

The primary purpose of compacting engineered fills is to expel water and air from the soil matrix to achieve an increase in stiffness, thus reducing the risk of post-construction settlement (Ewers 2006. This is typically measured for compliance using dry density ratio (field density/MDD). However, the moisture-density curve of sandy soils used to determine the MDD can give results that are difficult to interpret, such as those represented in Figure 5.2 for poorly-graded sands.

Figure 5.2: Moisture-density curve of poorly graded sands from Modified Proctor compaction (ASTM D1557)



Source: Arcement and Wright (2001).

The irregular development of the moisture-density curve for sandy soils may be attributed to negative pore-pressure and the anti-lubrication effect. In curves of sandy soils, high densities may be obtained at zero moisture content and under these circumstances water acts like an anti-lubricant. At low moisture contents, negative pore-pressure can also impact the compaction of sands as some menisci begin to form because only a small portion of the water is absorbed by the particles. The addition of more water causes the negative pore-pressure and anti-lubrication effects to balance. Then upon the addition of more water, lubrication proceeds and the particles slide over one another, increasing the dry density. This progresses until enough water is added so that it begins to displace the soil particles, at max dry density. Then density decreases as water displaces the soil particles (Lee & Suedkamp 1972).

One method of measuring the density or degree of compaction for cohesionless soils is the relative density method. This is based on the standard tests to determine maximum and minimum index density using a special vibratory table (Arcement & Wright 2001). However, the relative density method is not typically adopted by road agencies to measure and control the density of cohesionless soils because of the poor reproducibility of tests for maximum and minimum index density among laboratories. In particular, the maximum index density procedure may yield differences in results between laboratories as different vibratory tables are often used, and the tables are difficult to calibrate (Arcement & Wright 2001). As such, it was recommended that MDD for cohesionless soils is determined using the modified proctor standard test method (ASTM D1557).

Similarly, a study conducted by Hamidi, Varaksin and Nikraz (2013) into the reliability and reproducibility of the relative density concept found that, due to its formulation, relative density is prone to errors with magnitudes in the tens of per cent. This is because, and in accordance with ASTM D4253, the maximum index density may be determined using four methods; two are oven-dried and two are on wet soil. ASTM notes that wet methods can yield significantly higher values of maximum index density/unit weight for some soil. Thus, when considered with the minimum index density will significantly alter the value of relative density (Hamidi et al. 2013).

The review of available literature did not indicate any suitable alternatives to the use of MDD for density compliance of cohesionless soils.

5.5 Summary and Recommendations

A review of current national and international guidelines and literature in relation to the use of the maximum and minimum density for cohesionless sands was undertaken for consideration as an alternative for the MDD test. Findings from the literature review include:

- The irregular development of the moisture-density curve for sandy soils may be attributed to negative pore-pressure and the anti-lubrication effect.
- One method of measuring the density or degree of compaction for cohesionless soils is the density index (relative density) method.
- Australian standard test methods have been developed for the determination of density index for cohesionless soils based upon ASTM test methods.
- TMR is the only Australian road agency that specifies that the density index method shall be used for density compliance of compacted cohesionless sands.
- Relative density method is not typically adopted by road agencies to measure and control the density of cohesionless soils because of the poor reproducibility of tests for maximum and minimum index density among laboratories and its formulation.
- A review of the literature did not identify any suitable alternatives to the use of the MDD for density compliance of cohesionless soils.

Therefore, based on the literature findings, it is not recommended that the density index method for cohesionless soils be adopted by MRWA at this stage. Further research into laboratory evaluations may be undertaken by MRWA to determine the repeatability and reproducibility of MDD determinations with Western Australian cohesionless sands. This should also include evaluating maximum and minimum density determinations using current vibratory tables and calibrations for frequency and amplitude.

6 INTELLIGENT COMPACTION SYSTEMS FOR QC

6.1 Introduction

Ensuring compaction of the subgrade is completed to the required quality and consistency, MRWA surveillance officers attend construction sites to record and document compaction processes including number of passes, vibration frequency, and other equipment information. The implementation of intelligent compaction (IC) technologies may reduce the need for surveillance officers to attend all sites and would allow in-depth documentation of QC data relating to compaction works.

6.2 Intelligent Compaction Technology

IC is a compaction technology used for materials including, soils, aggregates and asphalt. IC allows the operator to measure real-time material properties during compaction, track progress visually, record measured data and machine settings digitally and report field data using rollers equipped with a number of measurement devices. Typically, the vibratory IC rollers are equipped with auto-feedback systems which feed processed data in real time for the roller operator to monitor using on-board computers (Chang et al. 2014).

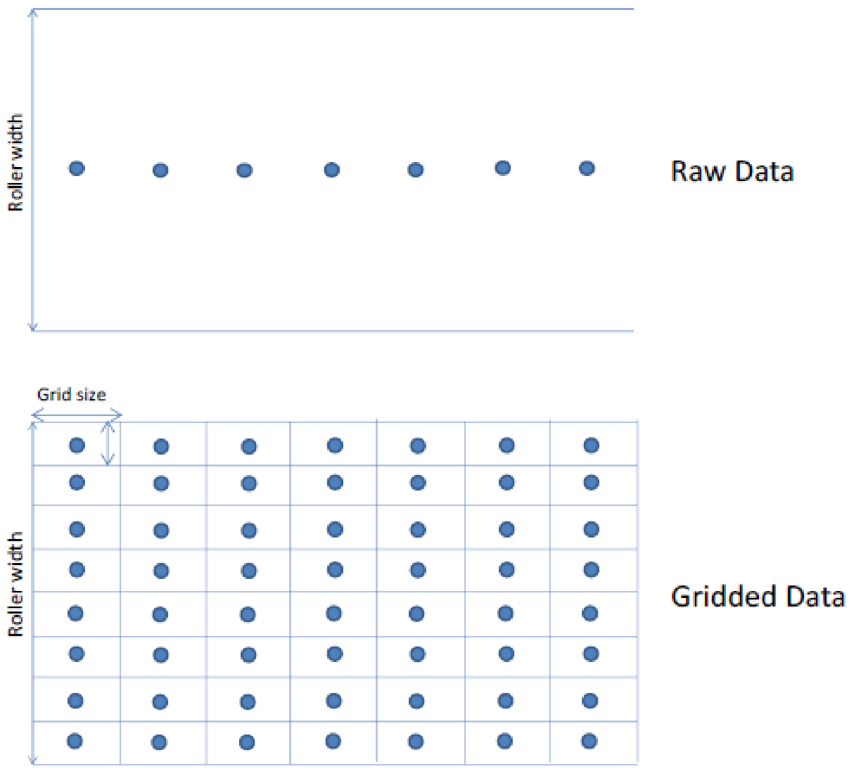
By utilising survey-grade global position systems (GPS), the precise location of the roller, speed and number of passes over a given area, may be mapped. These systems are commonly used to establish grade and to control other pieces of equipment (Chang et al. 2011). Compaction effort, frequency, amplitude and compaction material response is monitored using compaction meters or accelerometers and these readings are used to determine the effectiveness of the compaction process. Additionally, asphalt IC rollers have temperature instrumentation sensors installed to monitor the surface temperature of asphalt (Chang et al. 2011).

These measurements are referred to as IC measurement values (ICMV) and are collected from a single point at the centre of the front drum. The premise of ICMV is that the ICMV are related to traditional compaction measurements and used as part of effective earthwork or pavement compaction operations and QA/QC practices. Relative to GPS data collection, accurate and consistent data is essential, where the following capabilities for the roller GPS systems are required (Chang et al. 2011):

- Real-time kinematic (RTK) GPS systems, recommended for use on moving IC roller or hand-held rovers to measure locations in real time with accuracy with 10–30 mm. This level of precision is achieved by receiving correction signals transmitting from one or multiple onsite GPS base stations or virtual reference stations (VRS).
- A system that reports and records values in Northing and Easting, with vertical position reported in meters, in accordance with Universal Transverse Mercator (UTM) coordinates for the project site.
- A GPS base station operating at 900 MHz (recommended) or VRS and internet-based connection signals.
- If an offset is necessary between the GPS antenna and centre of front drum it must be entered and validated.

Data obtained from the IC process is typically stored in two different forms; raw data and gridded data. Raw IC data is recorded during compaction operations, typically using one data point at the bottom centre of the drum at a point in time (10 Hz or approx. 300 mm/sec). Gridded data is the raw data once it has been processed (sometimes in real time) to produce a data mesh over the drum width at a 300 mm by 300 mm grid, often by duplicating data points, as illustrated in Figure 6.1. The gridded data can be in two sub-forms; all passes data, which includes all passes within a given mesh and proofing data, which only includes the last passes within a given mesh (Chang et al. 2011).

Figure 6.1: Raw data vs. gridded data



Source: Chang et al. (2014).

6.3 Literature Review

In a comparative analysis of QC data collected from an IC roller with QA data collected from several hand-held field-testing devices, Camargo et al. (2006) found that IC had potential for use as a QC tool during construction. However, one of the noted challenges in implementing IC technology is handling the substantial amount of data generated and ensuring they are in usable formats for field inspectors. It was recommended roadway alignment is imported in ArcMaps and roller data is overlaid. Similarly, White et al. (2007) found that IC technology provides an opportunity to collect and evaluate information for 100% of the project area which may be managed by the use of ArcGIS.

One study by Chang et al. (2011) aimed to demonstrate, field test and compile information regarding soil/subbase and hot mix asphalt (HMA) IC technologies for the development of QC specifications. Relative to the management of the data collected during the IC process, Chang et al. (2011) recommended that all data should be associated with accurate GPS measurements (typically survey grade GPS) and in accordance with proper guidelines for GPS referencing (UTM zone), machine settings, electronic filename designation and data export. Furthermore, it is essential that geospatial analysis of IC data is conducted to evaluate spatial uniformity and other statistical characteristics and it is envisaged to be a basis for IC acceptance in the future. The major findings of the project relative to the benefits of IC technologies for QC include:

- IC can provide the necessary means to maintain a consistent rolling pattern by tracking roller passes.
- IC technologies can be especially beneficial to maintain consistent rolling patterns under lower visibility conditions (night time paving).
- Implementation will have an influence on the responsibilities of personnel at various stages of pavement constructions, eventually improving the quality and consistency of pavement products.

In 2014, the Federal Highway Administration (FHWA) published a report titled, *A Study on Intelligent Compaction and In-Place Asphalt Density* (Chang et al. 2014) focussing on determining whether IC measurements could be substituted for core data as a basis of acceptance. Relative to the implementation of IC technology for QC, the following conclusions were made:

- Prior to construction, GPS validation is essential to ensure all positioning system referencing and measurements are consistent.
- Use of ground-based GPS stations or virtual GPS base stations can successfully provide high precision positioning, although correct set up and checking are vital. Laser-based techniques (Total Station) can supplement positioning measurements.
- UTM is recommended to be the choice of GPS coordinate system.
- IC data transfer should be performed on a daily basis and the data checked for quality.
- Current IC technology can be readily used for method-based acceptance such as roller pass counts and coverage.

6.4 Review of Practice in the USA

The extent and depth of research into the development of IC technology in the USA has led to the adoption of IC in a number of state departments of transportation (DOT). Although focussing on earthwork construction, it is important to note that work has also been undertaken on the compaction of asphalt using IC technologies.

The relevant US practice guidelines and specifications reviewed are presented in Table 6.1.

Table 6.1: US practice documentation reviewed

Agency	Documents reviewed
American Association of State Highway and Transportation Officials (AASHTO)	PP81-18 *Standard Practice for Intelligent Compaction Technology for Embankment and Asphalt Pavement Applications* (AASHTO 2018a)
Federal Highway Administration (FHWA)	*Intelligent Compaction for Soils* (FHWA 2014)
Georgia Department of Transportation (GADOT)	*Intelligent Compaction for Soils* (GADOT 2012)
Indiana Department of Transportation (INDOT)	*Quality Control/Quality Assurance, QC/QA, Soil Embankment* (INDOT 2014)
Iowa Department of Transportation (IADOT)	*Special Provisions for Intelligent Compaction – Embankment* (IADOT 2010)
Kentucky Transport Cabinet (KTC)	*Special Note for Intelligent Compaction of Aggregate Bases and Soils* (KTC 2015)
Michigan Department of Transportation (MIDOT)	*Special Provision for Intelligent Compaction Mapping of Subbase and Aggregate Base* (MIDOT 2013)
Minnesota Department of Transportation (MnDOT)	*Quality Management Special – Intelligent Compaction* (MnDOT 2016) *Advanced Materials and Technology Manual: Chapter 3 – Construction Technologies and Procedures: Intelligent Compaction* (MnDOT 2018)
North Carolina Department of Transportation (NCDOT)	*Intelligent Compaction* (NCDOT 2012)
Texas Department of Transportation (TxDOT)	*Intelligent Compaction of Soil and Flexible Base* (TxDOT 2014)
Vermont Agency of Transportation (VTrans)	*Intelligent Compaction for Subbase and Reclaimed Stabilized Base (RSB) Applications* (Vermont Agency of Transportation 2014).

6.4.1 American Association of State Highway and Transportation Officials

AASHTO has developed a national specification for IC, PP 81-18: *Standard practice for intelligent compaction technology for embankment and asphalt pavement applications* (AASHTO 2018a), first published in 2014 as a provisional standard, which covers the requirements for compaction of both roadway embankments and asphalt using IC. Generally, this includes the equipment and construction requirements and the report data as summarised in Table 6.2.

However, it is important to note that the information contained within PP 81-18 (AASHTO 2018a) is general in nature and details regarding practice are not typically specified.

Table 6.2: Summary of AASHTO IC specifications for embankments

Equipment	Data outputs	Construction requirements	Report
▪ The contractor shall provide one survey grade GPS rover receiver and receiver kit. ▪ GPS setup to reference local, ground-based base station or the network RTK used on the project. ▪ IC rollers used for embankments shall be self-propelled, vibratory, smooth single-drum, smooth pad foot double-drum rollers or pneumatic rollers. ▪ IC rollers shall include an integrated on-board documentation system that can display real-time colour-coded maps of ICMVs – including location of the roller, number of passes, roller speeds, vibratory frequency and amplitude of roller drums. ▪ Display unit shall be capable of transferring data to cloud storage. ▪ IC roller equipment accuracy (GPS, speed, frequency, amplitude and temperature).	▪ Section title. ▪ Machine manufacturer, type, model, drum width, drum diameter and weight. ▪ Name index of ICMV. ▪ Unit index for ICMV. ▪ Reporting resolution for independent ICMVs – 90 degrees to the roller moving direction. ▪ Reporting resolution for independent ICMVs – in roller moving direction. ▪ UTM zone. ▪ Offset to coordinate universal time (UTC) (hrs). ▪ Number of IC data points. ▪ Date/time stamp. ▪ Longitude and longitude, including easting and northing. ▪ Height. ▪ Roller pass number, direction, speed, vibration, frequency and amplitude. ▪ Surface temperature (HMA only). ▪ ICMV.	▪ Training and certification of personnel shall include an IC supervisor, roller operator and IC support staff. ▪ Site analysis, setup and calibration shall occur at least 7 working days prior to the use of IC rollers for roller certifications and measurement passes. ▪ Approval of IC rollers for use, varying with soil/material type. ▪ Measurement pass information and IC roller setting (amplitude, frequency, speed). ▪ GPS coordinates and boundaries of the daily production area shall be reported daily. ▪ Submission of measurement pass data shall be transferred from the roller to the cloud at least once per day.	▪ Survey marker data (marker ID, XYZ coordinates, county, accuracy, condition). ▪ Boundaries of corrective action areas reports. ▪ Failing proof rolling reports. ▪ Boundaries of daily production areas and exceptions report.

Source: adapted from AASHTO (2018a).

6.4.2 Federal Highway Administration

In 2011, the FHWA published the report for a multi-year project aimed at assisting state departments of transportation in the development of QC specifications for IC technologies for subgrade, subbase and HMA pavement materials (Chang et al. 2011). This included the development of a generic IC specification for soils for state DOTs to modify as applicable, which was later published in 2014, *Intelligent compaction technology for soils applications* (FHWA 2014).

This generic specification aims to facilitate the implementation of IC technology and outlines the requirements for the IC equipment, construction, data analysis software and QC plan as summarised in Table 6.3. Notably, the equipment and data output requirements are similar to those specified by AASHTO (2018a).

Table 6.3: Summary of FHWA IC specification for soils

Equipment	Data outputs	QC plan
▪ IC rollers shall be smooth or padfoot single-drum vibratory rollers equipped with accelerometers. ▪ The output from the roller is designated as the ICMV. ▪ GPS radio and receiver units shall be mounted on each IC roller to monitor the drum locations and track the number of passes of the rollers. ▪ IC rollers shall include an integrated on-board documentation system that can display real-time colour-coded maps of ICMVs – including location of the roller, number of passes, roller speeds, vibratory frequency and amplitude of roller drums. ▪ Display unit shall be capable of transferring data by means of a USB port. ▪ On-board printer capable of printing the identity of the roller, date of measurements, construction area being mapped, percentage of the construction area mapped, target ICMV and areas not meeting ICMV. ▪ High precision positioning system (HPPS) to achieve accurate and consistent HPPS measurements among all HPPS devices on the same project – including all GPS and UTC data. ▪ Contractor shall provide the GPS system (including GPS receivers on IC rollers and hand-held GPS receivers (rovers) that makes use of the same reference system that can be a ground-based base station or network-RTK, to achieve RTK-GPS accuracy.	▪ Section title. ▪ Machine manufacturer, type, model, drum width, drum diameter and weight. ▪ Name index of ICMV. ▪ Unit index for ICMV. ▪ Reporting resolution for independent ICMVs – 90 degrees to the roller moving direction. ▪ Reporting resolution for independent ICMVs – in roller moving direction. ▪ UTM zone. ▪ Offset to UTC (hrs). ▪ Number of IC data points. ▪ Date/time stamp. ▪ Longitude and longitude, including easting and northing. ▪ Height. ▪ Roller pass number, direction, speed, vibration, frequency and amplitude. ▪ Surface temperature (HMA only). ▪ ICMV.	▪ Contract specific document describing how contractor will control materials, equipment and construction operations. ▪ The contractor shall coordinate and provide on-site training for contractors and agency project personnel related to operation of the IC technology for a recommended duration of 4−8 hours. ▪ Include GPS check testing of IC rollers, test sections (at least 75 m long and 8 m wide), monitoring construction operations and download and analysis of IC data. ▪ Detailed procedure for correlating and verifying GPS for the IC roller(s) and rover(s). ▪ Detailed plan and procedure for the construction of the test section to establish target compaction pass counts and target values for the strength of the materials using the standard testing devices. ▪ Procedures or monitoring of construction operations and IC rollers during production (i.e. number of roller passes and required level of compaction). ▪ Density/compaction – identification of the standard testing devices and frequency for monitoring and measuring the in-place density of the soil materials. Frequency in accordance with regular specs. ▪ Process and procedure for downloading and analysis of IC data from the roller. Minimum of twice per day during fill construction operations.

Source: adapted from FHWA (2014).

6.4.3 State Departments of Transportation

There are a number of US state DOTs that have published specifications regarding the IC technologies for QC/QA for soils. Notably, these specifications are generally based upon the FHWA (2014) and AASHTO (2018a) specifications, where specific construction requirements and equipment accuracy tolerances may vary between state DOTs. Currently, nine DOTs have published specifications for soil compaction using IC, while 23 DOTs specify IC for asphalt QA/QC.

Table 6.4 summarises and compares the state DOT IC specifications, where notable variations from the FHWA and AASHTO specifications are noted. General observations from the review of state DOT specifications include:

- IC system requirements (equipment and data outputs) generally the same for each jurisdiction although accuracy tolerances may vary between jurisdictions.
- Some specifications include a list of approved or recommended IC roller brands and models.
- QC plans are contract-specific and must be submitted by the contractor the DOT for approval.
- IC training is generally specified by each jurisdiction; however, length of training may vary.

Table 6.4: Comparison of state DOT specifications regarding using IC for soil QC

Jurisdiction	Equipment	Data outputs	QC plan	Notes
GADOT	As per FHWA (2014) and AASHTO (2018a)*	As per FHWA (2014) and AASHTO (2018a)*	As per FHWA (2014)*	▪ Contractor shall coordinate for on-site technical assistance from the IC roller manufacturer during the initial seven days of production, and as needed thereon.
INDOT	As per FHWA (2014) and AASHTO (2018a)	As per FHWA (2014) and AASHTO (2018)	As per FHWA (2014)	▪ Test sections shall be approx. 70 m long and 7 m wide with a thickness of up to 300 mm. ▪ Construction area must be between 1 500–22 860 m^2 and may extend over multiple days of operation. ▪ Procedure for selecting the appropriate IC roller based on the soil type shall be included in the QCP.
IADOT	Similar to FHWA (2014) and AASHTO (2018a)*	Similar to FHWA (2014) and AASHTO (2018a)*	Similar to FHWA (2014)*	▪ Includes pre-construction (classroom) training on IC, followed by a field training for the first two working days of IC usage. ▪ Test sections shall be a minimum of 75 m long and 5 m wide.
KTC	Similar to FHWA (2014) and AASHTO (2018a)	Similar to FHWA (2014) and AASHTO (2018a)	Similar to FHWA (2014)	▪ Work shall not begin until an acceptable GPS correlation and verification has been established. The DOT shall conduct random GPS verification testing to ensure data locations are accurate, at least once per week.
MIDOT	Similar to FHWA (2014) and AASHTO (2018a)*	Similar to FHWA (2014) and AASHTO (2018a)*.	Similar to FHWA (2014)	▪ IC training shall include two consecutive days of training, one day of classroom training and one day of field training within the limits of the project including both DOT and contractor staff. ▪ Test sections shall be minimum of 30 m long and 6 m wide and within the project limits.
MnDOT	Similar to FHWA (2014) and AASHTO (2018a)	Similar to FHWA (2014) and AASHTO (2018a)	Similar to FHWA (2014)	▪ Onsite IC support and operators shall be trained at least once per calendar year, prior to the use of IC rollers. ▪ Test sections shall be minimum of 100 m long and 2 m wide and within the project limits. IC is recommended for use when the following project/site conditions are met: ▪ Plant and equipment (i.e. GPS) meet specifications. ▪ Net lane length is greater than 6.5 km. ▪ Cellular coverage is sufficient, to allow transfer of data to the cloud at least once per day.
NCDOT	Similar to FHWA (2014) and AASHTO (2018a)*.	Similar to FHWA (2014) and AASHTO (2018a)*	Similar to FHWA (2014)*	▪ IC training shall include two consecutive days of training, one day of classroom training and one day of field training. ▪ The first test section must be constructed within the 14 days of beginning earthwork operations. ▪ Test sections shall be a minimum of 150 m long and 30 m wide, with a thickness up to 600 mm.
TxDOT	Similar to FHWA (2014) and AASHTO (2018a)	Similar to FHWA (2014) and AASHTO (2018a)	Similar to FHWA (2014)	▪ IC training shall be provided to personnel of all levels that will be associated with IC roller operation and a producer representative shall remain on site for the first two days of operation. ▪ At least one test section shall be compacted to a minimum length of 150 m and the full width of the material course. ▪ IC data from the test section shall be used to proof map the area and generate a colour-coded map based on ICMV data.
VTrans	As per FHWA (2014) and AASHTO (2018a)	As per FHWA (2014) and AASHTO (2018a)	Similar to FHWA (2014)	▪ IC roller data shall be supplied to the engineer at least two times each data of compaction, representing approx. half of the mapping for each day. ▪ Test sections shall be approx. 30 m long and 6 m wide, with a thickness up to 300 mm. ▪ A minimum of 90% of the construction area shall be mapped.

* Although published prior to FHWA (2014) and AASHTO (2018a).

- Field and acceptance requirements vary between jurisdictions but generally include GPS field validation, mapping, test strips, spot testing and operation criteria.
- QC generally requires all-passes data to be submitted daily.

6.5 Summary and Recommendations

A literature review was undertaken to determine whether IC technologies were able to accurately record and document compaction processes for QC purposes. It is important to note that there are relatively few studies focussing on how the implementation of IC technologies may be used to allow in-depth documentation of QC data relating to compaction works, as studies primarily focus on correlating IC values to traditional methods of density compliance for QA. However, several US state DOTs have specified the use of IC technology for QC. Furthermore, it is important to note that the literature reviewed was US-based as local and other international literature could not be sourced. General findings resulting from the review include:

- IC technology utilises survey-grade GPS to track the precise location of the roller, speed and number of passes over a given area.
- Compaction meters or accelerometers mounted at a single point at the centre of the front drum of the roller are used to monitor compaction effort, frequency, amplitude and material response. Rollers may also be equipped with temperature sensors for asphalt applications.
- IC technology can provide the means to maintain a consistent rolling pattern by tracking roller passes and settings.
- In the USA, there has been a number of state DOTs that have specified the use of IC technologies for QC.
- Current IC technology may be readily used for QC.

Considering the findings of the literature review and the documentation of compaction processes for QC, it is recommended that MRWA considers undertaking trials with IC technologies to identify the accuracy of reported data and maturity of IC technology.

7 CONCLUSIONS AND RECOMMENDATIONS

This project was undertaken to conduct a review of national and international current practice relative to subgrade and embankment construction to identify areas for improvement within the current density compliance process, and to develop and employ new techniques. This considered a range of technical requirements of the current MRWA guidance. A summary of the conclusions reached, and suggested actions include:

- Nuclear moisture density alternatives for compaction QA/QC of sand subgrades and embankments:
  - The literature indicates that several non-nuclear compaction devices have the potential to replace the NDM as a field density QA/QC tool.
  - It is recommended that the LFWD and other selected alternative devices identified in this report with high ratings are assessed to determine whether they can be used as a non-nuclear alternative to the sand replacement test or the NDM.
- Alternative, non-destructive methods to assess dry-back of constructed subgrades:
  - Evaluation of the alternative test methods indicates that there are several potential non-destructive options for assessing subgrade and embankment dry-back.
  - It is recommended that moisture content determination using the NDM undergo evaluation as a non-destructive alternative to the convection oven method.
  - Furthermore, it is recommended that field evaluations of selected non-destructive, non-nuclear devices identified in this report with high ratings are compared to current MRWA practice using the convection oven to assess suitability for adoption.
- Method specification framework for PSP and density QC:
  - The PSP is typically only used on two types of materials – Perth sands and select fill material – and contractor method specification submissions vary and often do not include the necessary information required for a complete calibration.
  - It is recommended that the proposed framework and corresponding submissions checklist is trialled in future construction projects to determine its suitability and applicability for practical use and to determine whether or not it improves the quality of the PSP method specification submissions.
- Specification of maximum and minimum density for sands:
  - The Australian standard test method for the determination of density index for cohesionless soils is only adopted by one road agency in Australia (TMR).
  - Taken together, these findings do not support recommendations for the adoption of density index method for cohesionless soils unless laboratory evaluations are undertaken to determine the repeatability of test results.
- Intelligent compaction systems for QC:
  - The literature review identified that current IC technology can track the precise location of the roller, speed and number of passes over a given area as well as the compaction effort, frequency, amplitude, material response and temperature (for asphalt). This data can be readily used for QC.

— These findings suggest that MRWA should consider undertaking trials with IC technologies to identify the accuracy of the data reported during the compaction process.

REFERENCES

Abyad, J 2016, 'Determination of non-nuclear alternative to the nuclear density gauge through laboratory and field testing', MEng thesis, Rowan University, Glassboro, NJ, USA.

Anderson, N 2014, *Testing and assessment of portable seismic property analyzer,* NUTC R297, Centre for Transportation Infrastructure and Safety, Rolla, MO, USA.

Arcement, BJ & Wright, SG 2001, *Evaluation of laboratory compaction procedures for specification of densities for compacting fine sands,* FHWA/TX-02/1874-1, Federal Highway Administration, Washington, DC, USA.

Association Francaise de Normalisation 2012, *Soils: investigation and testing – inspection of compaction quality – method using a variable energy dynamic penetrometer – principles and method for calibrating the penetrometer – exploitation of results – interpretation,* (in French), NF P 94-105, AFNOR, Paris, France.

Australian Radiation Protection and Nuclear Safety Agency 2004, *Code of practice and safety guide: portable density/moisture gauges containing radioactive sources,* ARPANSA, Melbourne, Vic.

Austroads 2014, *Characterisation and performance evaluation of granular bases project: pavement construction report,* AP-T267-14, Austroads, Sydney, NSW.

Austroads 2017, *Guide to pavement technology part 2: pavement structural design*, AGPT02-17, Austroads, Sydney, NSW.

Berney, ES & Kyzar, JD 2012, 'Evaluation of non-nuclear soil moisture and density devices for field quality control', *Transport Research Board annual meeting, 91st, 2012, Washington, DC, USA,* TRB, Washington, DC, USA.

Berney, ES, Kyzar, JD & Oyelam, LO 2011, *Device comparison for determining field soil moisture content*, ERDC/GSL TR-11-42, United States Army Corps of Engineers, Vicksburg, MS, USA.

Berney, ES, Meijias-Santiago, M & Kyzar, JD 2013, *Non-nuclear alternatives to monitoring moisture-density response in soils,* ERDC/GSL TR-13-6, United States Army Corps of Engineers, Vicksburg, MS, USA.

Camargo, F, Larsen, B, Chadbourn, B, Roberson, R & Siekmeir, J 2006, 'Intelligent compaction: a Minnesota case history', *Annual University of Minnesota Geotechnical Conference, 54th, 2006, Maplewood, MN, USA,* Minnesota Department of Transportation, Maplewood, MN, USA.

Chang, G, Xu, Q & Rutledge, J 2011, *Accelerated implementation of intelligent compaction technology for embankment subgrade soils, aggregate base, and asphalt pavement materials,* Report no. FHWA-IF-12-002, Federal Highway Administration, Washington, DC, USA.

Chang, G, Xu, Q, Rutledge, J & Garber, S 2014, *A study of intelligent compaction and in-place asphalt density,* Report no. FHWA-IHF-14-017, Federal Highway Administration, Washington, DC, USA.

Clegg, B 1979, 'Penetrometer application, sands, Perth', *Diamond Jubilee Conference, 1979, Perth, WA,* Institution of Engineers, Australia, Sydney, NSW, pp. 56–62.

Coman-Walton, A & Fahey, M 2009, 'Effect of depth on results from the Perth sand penetrometer test', *Australian Geomechanics,* vol. 44, no. 2, pp. 25–40.

Department of Infrastructure, Planning and Logistics 2017, *Standard specification for roadworks,* DIPL, Darwin, NT.

Department of Planning, Transport and Infrastructure 2017, *Construction of earthworks,* Specification part R10, DPTI, Adelaide, SA.

Department of State Growth 2012, *Earthworks,* Roadworks Specification R22, DOSG, Hobart, Tasmania.

Durham, GN 2005, 'Using TDR technology for earthwork compaction quality control', *Presentation to the California Geotechnical Engineers Association*, *2005, Orange County, CA, USA,* CalGeo, CA, USA.

Ewers, B 2004, 'Relative compaction: in search of a rational method for specification', *Australian Geomechanics,* vol. 41, no. 3, pp. 155–160.

Federal Highway Administration 2014, *Intelligent compaction technology for soils applications,* FHWA, Washington, DC, USA.

Georgia Department of Transportation 2012, *Intelligent compaction of soils,* GADOT, Atlanta, Georgia, USA.

Glick, GL & Clegg, B 1965, 'Use of a penetrometer for site investigation and compaction control at Perth, W.A.', *Civil Engineering Transactions,* Institution of Engineers, October 1965, pp. 114–8.

Hamidi, B, Varaksin, S & Nikraz, H 2013, 'Relative density concept is not a reliable criterion', *Proceedings of the Institution of Civil Engineers: Ground Improvement*, no. 166, pp. 78–85.

Hanson, BJ & Nieber, JL 2013, *Performance-based measurement of optimum moisture soil compaction,* MN/RC 2013-28, Minnesota Department of Transportation, St. Paul, MN, USA.

Humboldt 2014, *H-4140 GeoGauge product manual,* Humboldt, Elgin, IL, USA.

Humboldt n.d., *H-4112 Percometer,* Humboldt, Elgin, IL, USA.

Idaho Transportation Department 2015, *Review of non-nuclear density gauges as possible replacements for ITD's nuclear density gauges,* RP 210, ITD, ID, USA.

Indiana Department of Transportation 2014, *Quality control/quality assurance, QC/QA, soil embankment,* INDOT, Indianapolis, Indiana, USA.

Iowa Department of Transportation 2010, *Special provisions for intelligent compaction – embankment,* IADOT, Ames, Iowa, USA.

James Instruments 2019, *Trident hand held microwave moisture meter for fine and coarse aggregates,* webpage, James Instruments, Chicago, IL, USA, viewed 3 April 2019, <https://www.ndtjames.com/Trident-p/t-t-old.htm>.

Kentucky Transport Cabinet 2015, *Special note for intelligent compaction of aggregate bases and soils,* KTC, Pikeville, Kentucky, USA.

Ladd Research Industries 2018a, *Digital low temperature forced air ovens,* webpage, LRI, Williston, VT, USA, viewed 3 April 2019, <https://www.laddresearch.com/general-laboratory-supplies/ovens/digital-low-temperature-forced-air-ovens>.

Ladd Research Industries 2018b, *LRS-232 microwave oven process controller,* webpage, LRI, Williston, VT, USA, viewed 3 April 2019, <https://www.laddresearch.com/general-laboratory-supplies/small-equipment-instruments/laboratory-microwave-ovens/microwave-oven-process-controller>.

Lee, J, Lacey, D & Look, B 2017, 'P60: Best practice in compaction QA for pavement and subgrade materials (year 1 – 2016/2017)', PRP16036, ARRB Group, Vermont South, Vic.

Lee, P & Suedkamp, R 1972, 'Characteristics of irregularly shaped compaction curves of soils', *Highway Research Record,* no. 381, pp. 1–9.

Main Roads Western Australia 2008, *Statistically based quality control for density in road construction,* Engineering road note 8, MRWA, Perth, WA.

Main Roads Western Australia 2011a, *Soil and granular pavement material moisture content: convection oven method,* Test method WA 110.1, MRWA, Perth, WA.

Main Roads Western Australia 2011b, *Soil and granular pavement material moisture content: microwave oven method,* Test method WA 110.2, MRWA, Perth, WA.

Main Roads Western Australia 2011c, *Sampling procedures for soil and manufactured granular materials,* Test method WA 100.1, MRWA, Perth, WA.

Main Roads Western Australia 2011d, *Particle size distribution abbreviated method for coarse and medium grained soils,* Test method WA 115.2, MRWA, Perth, WA.

Main Roads Western Australia 2012a, *Dry density ratio (percent),* Test method WA 134.1, MRWA, Perth, WA.

Main Roads Western Australia 2012b, *Dry density/moisture content relationship: modified compaction coarse grained soils,* Test method WA 133.2, MRWA, Perth, WA.

Main Roads Western Australia 2012c, *Dry density: sand replacement method,* Test method WA 324.1, MRWA, Perth, WA.

Main Roads Western Australia 2012d, *Moisture ratio (percent),* Test method WA 136.1, MRWA, Perth, WA.

Main Roads Western Australia 2013a, *Determination of field density: nuclear method,* Test method WA 324.2, MRWA, Perth, WA.

Main Roads Western Australia 2013b, *Procedure for the design of road pavements: Western Australian supplement to the Austroads guide to pavement technology part 2: pavement structural design*, Engineering road note 9, MRWA, Perth, WA.

Main Roads Western Australia 2014, *Calibration of nuclear density meters: standard density blocks,* Test method WA 135.1, MRWA, Perth, WA.

Main Roads Western Australia 2015, *Earthworks,* Specification 302, MRWA, Perth, WA.

Main Roads Western Australia 2017, *Dry density/moisture content relationship: modified compaction fine and medium grained soils,* Test method WA 133.1, MRWA, Perth, WA.

Main Roads Western Australia 2018a, *Pavements,* Specification 501, MRWA, Perth, WA.

Main Roads Western Australia 2018b, *Quality systems,* Specification 201, MRWA, Perth, WA.

Mehta, Y & Ali, A 2016, *Alternatives to nuclear density testing,* FHWA-NJ-2016-003, Federal Highway Administration, Washington, DC, USA.

Michigan Department of Transportation 2013, *Special provision for intelligent compaction mapping of subbase and aggregate base,* MIDOT, Lansing, Michigan, USA.

Minnesota Department of Transportation 2016, *Quality management special – intelligent compaction (IC) method,* MnDOT, Minneapolis, Minnesota, USA.

Minnesota Department of Transportation 2018, *Construction technologies and procedures*, Advanced Materials and Technology Manual Chapter 3, MnDOT, Minneapolis, Minnesota, USA.

Mohammadi, SD 2016, 'Use of a Perth sand penetrometer (PSP) device to determine the engineering parameters of sands', *Acta Geotechnica Slovenica,* vol. 13, no. 1, pp. 77–87.

Nazzal, M 2014, *Non-nuclear methods for compaction control of unbound materials,* Synthesis 456, Transportation Research Board, Washington, DC, USA.

Nebraska Transportation Center 2011, *Non-nuclear method for density measurements,* Report SPR1 (10) P335, NTC, Lincoln, NE, USA.

North Carolina Department of Transportation 2012, *Intelligent compaction,* NCDOT, Raleigh, North Carolina, USA.

Perth Sand & Dynamic Cone Penetrometers 2017 *Penetrometers,* webpage, PSDCP, Perth, WA, viewed 3 April 2019, <http://penetrometers.com.au/penetrometers>.

Pound Sterling Live 2019, *The Australian dollar to US dollar historical exchange rates conversion page for 2018,* webpage, PSL, London, UK, viewed 3 April 2019 <https://www.poundsterlinglive.com/best-exchange-rates/best-australian-dollar-to-us-dollar-history-2018>.

Queensland Department of Transport and Main Roads 2017, *Materials testing manual,* Edition 4, TMR, Brisbane, Qld.

Queensland Department of Transport and Main Roads 2018a, *General earthworks,* Main roads technical specification MRTS04, TMR, Brisbane, Qld.

Queensland Department of Transport and Main Roads 2018b, *Amendment register – 2014 to 2019,* TMR, Brisbane, Qld.

Queensland Department of Transport and Main Roads 2018c, *Nuclear gauge testing manual, Test Method N02: Material bias – soil moisture content,* Edition 3, Amendment 3, Section 3: Test methods, November.

Rathje, EM, Wright, SG, Stokoe, KH, Adams, A, Tobin, R & Salem, M 2006, *Evaluation of non-nuclear methods for compaction control,* Report FHWA/TX-06/0-4835-1, Federal Highway Administration, Washington, DC, USA.

Roads & Maritime Services 2012, *Density in-situ of road construction materials (fixed volume extractive method)*, Test method T165, RMS, Sydney, NSW.

Sebesta, S, Oh, J, Lee, SI, Sanchez, M & Taylor, R 2013, *Initial review of rapid moisture measurements for roadway base and subgrade,* FHWA/TX-13/0-6676-1, Texas Department of Transportation, Austin, TX, USA.

Standards New Zealand 2015, *Methods of sampling and testing road aggregates*, NZS 4407, Wellington, NZ.

Texas Department of Transportation 2014, *Intelligent compaction of soil and flexible base,* TxDOT, Austin, Texas, USA.

Transit New Zealand 2005, *Specification for construction of unbound granular pavement layers,* TNZ B/02:2005, TNZ, Wellington, NZ.

Vermont Agency of Transportation 2007, *Non-nuclear compaction gauge comparison study,* Report 2007-19, VTrans, Montpelier, VT, USA.

Vermont Agency of Transportation 2014, *Intelligent Compaction for Subbase and Reclaimed Stabilized Base (RSB) Applications,* Intelligent compaction Specification 2014, VTrans, Montpelier, VT, USA.

VicRoads 2017, *Acceptance of field compaction*, RC 500-05, VicRoads, Kew, Victoria.

Weber, JJ 2018, 'Compaction testing of granular materials', MEng thesis, South Dakota State University, Madison, SD, USA.

White, DJ, Vennapusa, P & Thompson, MJ 2007, *Field validation of intelligent compaction monitoring technology for unbound materials,* Iowa State University, IA, USA.

White, DJ, Thompson, MJ, Vennapusa, P & Siekmeier, J 2008, 'Implementing intelligent compaction specification on Minnesota TH-64', *Transportation Research Record: Journal of the Transportation Research Board,* no. 2045, pp. 1–9.

American Association of State Highway and Transportation Officials

AASHTO 2018a, *Standard practice for intelligent compaction technology for embankment and asphalt pavement applications*, PP81-18, AASHTO, Washington, DC, USA.

AASHTO T99-2018b, *Standard method of test for moisture-density relations of soils using a 2.5–kg (5.5–lb) rammer and a 305–mm (12–in.) drop.*

AASHTO T217-2014, *Standard method of test for determination of moisture in soils by means of a calcium carbide gas pressure moisture tester.*

AASHTO T310-2013, *Standard method of test for in-place density and moisture content of soil and soil-aggregate by nuclear methods (shallow depth).*

American Society for Testing and Materials International

ASTM D698-12e2, *Standard test methods for laboratory compaction characteristics of soil using standard effort (12,400 ft-lbf/ft^3(600 kN-m/m^3).*

ASTM D1195 / D1195M-09(2015), *Standard test method for repetitive static plate load tests of soils and flexible pavement components, for use in evaluation and design of airport and highway pavements.*

ASTM D1196 / D1196M-12(2016), *Standard test method for nonrepetitive static plate load tests of soils and flexible pavement components, for use in evaluation and design of airport and highway pavements.*

ASTM D1556 / D1556M-15e1, *Standard test method for density and unit weight of soil in place by the sand-cone method.*

ASTM D1557-12e1, *Standard test methods for laboratory compaction characteristics of soil using modified effort (56,000 ft-lbf/ft^3(2,700 kN-m/m^3))*

ASTM D2167-15, *Standard test method for density and unit weight of soil in place by the rubber balloon method.*

ASTM D2216-10, *Standard test methods for laboratory determination of water (moisture) content of soil and rock by mass.*

ASTM D2922-01, *Standard test methods for density of soil and soil-aggregate in place by nuclear methods (shallow depth).*

ASTM D4253-16, *Standard test method for maximum index density and unit weight of soils using a vibratory table.*

ASTM D4254-16, *Standard test method for maximum index density and unit weight of soils and calculation of relative density.*

ASTM D4643-17, *Standard test method for determination of water content of soil and rock by microwave oven heating.*

ASTM D4944-18, *Standard test method for field determination of water (moisture) content of soil by the calcium carbide gas pressure tester.*

ASTM D5874-16, *Standard test method for determination of the impact value (IV) of a soil.*

ASTM D6758-18, *Standard test method for measuring stiffness and apparent modulus of soil and soil-aggregate in-place by electro-mechanical method.*

ASTM D6780 / D6780M-12, *Standard test method for water content and density of soil in-situ by time domain reflectometry (TDR).*

ASTM D6951 / D6951M-18, *Standard test method for use of the dynamic cone penetrometer in shallow pavement applications*

ASTM D7698-11a, *Standard test method for in-place estimation of density and water content of soil and aggregate by correlation with complex impedance method.*

ASTM D7830 / D7830M-14, *Standard test method for in-place density (unit weight) and water content of soil using an electromagnetic soil density gauge.*

ASTM E2583-07(2015), *Standard test method for measuring deflections with a light weight deflectometer (LWD).*

ASTM E2835-11(2015), *Standard test method for measuring deflections using a portable impulse plate load test device.*

Standards Australia

AS 1289.2.1.1-2005 (R2016), *Methods of testing soils for engineering purposes – soil moisture content tests: determination of the moisture content of a soil – oven drying method (standard method).*

AS 1289.2.1.4-2005 (R2016), *Methods of testing soils for engineering purposes – soil moisture content tests: determination of the moisture content of a soil – microwave-oven drying method (subsidiary method).*

AS 1289.5.3.1-2004 (R2016), *Methods of testing soils for engineering purposes – soil compaction and density tests: determination of the field density of a soil – sand replacement method using a sand-cone pouring apparatus.*

AS 1289.5.3.2-2004 (R2016), *Methods of testing soils for engineering purposes – soil compaction and density tests: determination of the field dry density of a soil – sand replacement method using a pouring can, with or without a volume displacer.*

AS 1289.5.5.1-1998, *Methods of testing soils for engineering purposes – soil compaction and density tests: determination of the minimum and maximum dry density of a cohesionless material – standard method.*

AS 1289.5.6.1-1998 (R2016), *Methods of testing soils for engineering purposes – soil compaction and density tests: compaction control test – density index method for a cohesionless material.*

AS 1289.5.8.1-2007, *Methods of testing soils for engineering purposes – soil compaction and density tests: determination of the field density and field moisture content of a soil using a nuclear surface moisture-density gauge – direct transmission mode.*

AS 1289.6.3.2-1997 (R2013), *Methods of testing soils for engineering purposes – soil strength and consolidation tests: determination of the penetration resistance of a soil – 9kg dynamic cone penetrometer test.*

AS 1289.6.3.3-1997 (R2013), *Methods of testing soils for engineering purposes – soil strength and consolidation tests: determination of the penetration resistance of a soil – Perth sand penetrometer test.*

AS 1289.6.9.1-2000 (R2013), *Methods of testing soils for engineering purposes – soil strength and consolidation test: determination of stiffness of soil – Clegg impact value (CIV).*

APPENDIX A LITERATURE REVIEW: ALTERNATIVE QA COMPACTION METHODS

Table A 1: Alternative QA density test method literature review summary

Study	Traditional test methods	Alternative devices evaluated	Soils evaluated	Findings
Rathje et al. (2006)	▪ NDM	▪ PANDA ▪ Clegg Hammer ▪ DCP ▪ MDI ▪ EDG ▪ SQI ▪ PSPA	▪ High plasticity clay (CH) ▪ Low plasticity clay (CL) ▪ Well graded sand (SW) TxDOT type B ▪ Poorly graded gravel (GP) TxDOT type A ▪ Poorly graded gravel (GP) TxDOT type D	▪ Research was conducted using a field evaluation study of a number of non-nuclear methods for compaction control across five soil types in the USA. ▪ None of the alternative methods evaluated are currently feasible for replacing the NDM for in situ compaction control. ▪ DCP, Clegg Hammer and PSPA may provide a general assessment of compaction dry unit weight but do not provide precision for QA. ▪ PANDA, DCP, Clegg Hammer and PSPA do not measure moisture content. ▪ The MDI currently has issues with clayey soils and sandy soils, although improvements may increase viability in the future. ▪ The EDG has a complex calibration procedure and consistently displayed inaccurate moisture content readings for all soil types in the laboratory. Field testing was not conducted with the EDG as it could not be field calibrated. ▪ SQI appears to have a good theoretical basis for relating electrical soil properties to dry unit weight and if the manufacturer can develop a robust calibration procedure, the device may be useful in the future. It was not used for laboratory or field testing in this study.
Vermont Agency of Transportation (2007)	▪ NDM	▪ MDI ▪ EDG	▪ Subbase gravel ▪ Granular backfill ▪ Sand borrow ▪ Crusher run	▪ Two electrical devices were compared to the NDM using field testing in the USA. ▪ The EDG compared well with the NDM for dry density, especially with fine grained materials. ▪ Both the EDG and MDI exhibited a linear relationship R-value of 0.90, however, the MDI results showed consistently lower in-place dry density readings compared to the NDM. ▪ It was speculated that the process of driving spikes into the ground using the MDI may have loosened the compacted soil, resulting in a lower value of in-place dry density.
Nebraska Transportation Center (2011)	▪ NDM ▪ Sand cone ▪ Rubber balloon	▪ EDG ▪ LFWD	▪ Silt (loess) ▪ 'Brown dirt'	▪ Using laboratory and field testing, the study investigated new technologies for QA in the USA. ▪ The EDG and NDM have very similar results when unmodified and direct data are considered, but NDM performs better when correction factors are applied. There are no current methods to improve and correct EDG data. ▪ The LFWD also displayed similar results to the NDM when using raw data, although the NDM showed better correlation with the standard method when the data was corrected. ▪ With an improved methodology to create soil models for the EDG and standardized ways to develop the LFWD's target values, the EDG and LFWD could have a similar or better accuracy than the NDM.
Berney and Kyzar (2012)	▪ NDM ▪ Water balloon ▪ Sand cone	▪ Steel shot ▪ DCP ▪ EDG ▪ SDG	▪ Crushed limestone (GP-GM) ▪ Silty gravel (SM) ▪ Clay gravel (SP-SC) ▪ Silty sand (ML-2) ▪ Concrete sand (SP) ▪ Vicksburg silt (loess) ▪ Buckshot clay	▪ Seven test sections were constructed to facilitate field testing for each of the soil types and density/modulus devices in the USA. ▪ Experimental analysis found that the corrected SDG had the least variability in both the average density value for each soil and the least amount of high-low scatter from the average value. It was deemed the best substitute for the NDM. ▪ The EDG performed well but required a more complex calibration routine to establish accuracy. ▪ The steel shot had the greatest variability of the test methods evaluated. ▪ The uncorrected SDG showed considerably more variability than the EDG or sand cone test, indicating a lack of sufficient internal calibration for the soils tested. ▪ The electronic devices were deemed the most valuable due to their ability to capture both the moisture content and density of the soil with a single device.
Berney, Meijias-Santiago and Kyzar (2013)	▪ NDM ▪ Sand cone ▪ Water balloon	▪ Steel shot ▪ EDG ▪ SDG ▪ MDI ▪ LFWD (Dynatest) ▪ LFWD (Zorn) ▪ GeoGauge ▪ DCP ▪ Clegg Hammer	▪ Silty-sand (ML) ▪ Concrete sand (SP) ▪ Sandy silt (ML) ▪ Silty sand with gravel (SM) ▪ Sand with clay and gravel (SP-SC) ▪ Sand with silt and gravel (SP-SM) ▪ Buckshot clay (CH) ▪ Crushed limestone (GP-GM)	▪ A full-scale construction of seven soils was conducted to evaluate the effectiveness of alternative compaction QA devices in the USA. ▪ The SDG was the best device and overall had the best combination of accuracy and precision compared to the Troxler 3440 NDM. The SDG provides the best measure of accuracy but lacks precision, however the accuracy is highly dependent upon proper calibration with PSD and Atterberg limit properties. The SDG-corrected must be tuned to an average of two-three independent density measurements using a traditional density device. ▪ The EDG was the next best device for measuring soil density, having the best precision but only average accuracy compared to the NDM. The accuracy and precision is dependent on proper calibration points and is much more complex than the SDG, also resulting in greater measurement variability. ▪ The MDI was highly prone to error, showing errors for approximately 30% of readings across all soils. This may be attributed to the force required to break the guide plate loose from the probes while in the soil, resulting in a loosening of pins in the soil. ▪ The steel shot volume replacement device performed the poorest of all devices, exhibiting the greatest overall variability in accuracy and precision. ▪ The LFWD, DCP, Clegg Hammer and GeoGauge are not able to return a value of density or moisture content, nor do they correlate with moisture and density values returned by the NDM. These devices are ideally more suited to modulus-based specifications for soil performance. ▪ No correlations were found relating LFWD, DCP, Clegg Hammer and GeoGauge readings to measured density. If correlations can be found they may be considered alternatives to the NDM for QA/QC.
Nazzal (2014)	▪ NDM	▪ DCP ▪ Clegg Hammer ▪ GeoGauge ▪ LFWD ▪ BCD ▪ PSPA ▪ MDI ▪ EDG ▪ SDG	▪ Varies, study was primarily literature review	▪ This study involved a comprehensive synthesis and review of literature from a variety of US-based and other international studies relative to the use of non-nuclear methods for compaction control of unbound materials. ▪ It was found that studies related to electrical devices (MDI, EDG, SDG) indicated that the none of the technologies were recommended for use. All devices involved longer testing times than the NDM and more complex procedures. The EDG and MDI also had reported limitations for testing highly plastic clays and stiff soils. Limited studies have been conducted regarding the measurement of moisture content. ▪ The BCD, DCP and LFWD may not be suitable for very soft, fine grained soils. ▪ GeoGauge is extremely sensitive to seating conditions. Significant inconsistencies in testing data. ▪ The Clegg Hammer boundary has an impact during device calibration. Different Clegg Hammer models measure different impact values. ▪ The DCP is limited to use with materials with a maximum particle size smaller than 50 mm. ▪ The BCD has shallow depths, which may not allow them to assess the properties of the entire lift. ▪ Limiting the use of the PSPA, is the relatively high price compared to the NDM.

Study	Traditional test methods	Alternative devices evaluated	Soils evaluated	Findings
Abyad (2016)	▪ NDM	▪ BCD ▪ LFWD ▪ DCP	▪ Natural sand ▪ Dense graded aggregates ▪ Reclaimed concrete aggregates	▪ Evaluation was conducted through laboratory and field testing on a number of soils in the USA. ▪ The BCD testing indicates that the BCD is sensitive to changes in the moisture content. The modulus values for the DGA and RCA aggregates increased when the moisture content of the samples increased. However, this was inverse for natural sand materials. Trends may be attributed to the high variability of the BCD. ▪ Analysis of the results indicates that the BCD was not capable of capturing the differences in compaction efforts. The modulus values measured were statistically similar at all density levels. Significant differences were observed for the natural sand materials and DGA materials indicating BCD is sensitive to aggregate type. ▪ LFWD test results indicate that the modulus values for the natural sand and reclaimed concrete aggregates were similar at all moisture levels, indicating that the LFWD is not influenced by changes in the moisture of the sample. ▪ DCP testing indicate that the test is influenced by changes in moisture content within the samples. The DCP blow count decreased as moisture increased for all tested materials. ▪ DCP results also indicated that the number of DCP blows increased as the density level increased for all aggregate types, thus indicating that the DCP is sensitive to differences in compaction efforts applied between samples. ▪ DCP values for natural sand were lower than those measured for DGA and reclaimed concrete aggregate, indicating the DCP is also sensitive to aggregate type. ▪ The DCP is an adequate tool to replace the NDM and is highly dependent on aggregate moisture content and gradation characteristics (% passing 4.75 mm and 0.075 mm sieves). Draft implementation guidelines were developed for the DCP.
Idaho Transportation Department (2015)	▪ NDM ▪ Sand cone	▪ EDG ▪ SDG ▪ GeoGauge	▪ Fine sand subgrade ▪ Granular base ▪ Granular burrow ▪ Silt (loess) subgrade ▪ Clay subgrade ▪ Coarse fill ▪ Tan sand ▪ Black coarse sand ▪ Full-depth reclamation with emulsified asphalt ▪ Cement recycled asphalt base stabilised	▪ Field testing was conducted to evaluate alternative methods in the USA. ▪ The alternative devices did not agree well with the sand cone density values, which were highly variable and inconsistent. ▪ The GeoGauge modulus and stiffness values showed no consistent correlation with the density values and moisture contents for the sand cone or the NDM. ▪ Results from the EDG and NDM correlation (soil model) agreed well with NDM validation measurements based on statistical analysis. ▪ EDG results showed poor correlation with sand cone densities. ▪ The SDG readings produced the most favourable validation with the NDM density, sand cone density and oven moisture content values for the entire data set. ▪ EDG results showed good correlation with NDM readings for sand and fair correlation for granular but performed poorly for fine-grained soils. ▪ SDG had good moisture correlation with NDM readings for granular materials, but performed poorly in precisely determining moisture in fine-grained and sand material. ▪ EDG generally correlated well with the NDM soil model and the 3–point correlated SDG provided reasonable estimates of density and moisture contents. ▪ Gauges were often imprecise, especially in fine-grained soils and sometimes produced results with significant variance to those obtained using NDM and oven. ▪ The EDG showed the most promising results, however none of the alternative methods are recommended for QA compaction.
Mehta and Ali (2016)	▪ NDM	▪ BCD ▪ LFWD ▪ DCP ▪ GeoGauge	▪ Natural sand ▪ Dense graded aggregates ▪ Reclaimed concrete aggregates	▪ Based on the outcomes of literature and state road agency surveys, the DCP, LFWD and BCD were selected for lab and field evaluation in the USA. ▪ Based on the comparison of the standard error of the mean laboratory results, variability was similar for all non-nuclear devices tested. However, the DCP showed higher variability when the soils had moisture contents above the OMC. ▪ All test methods were able to distinguish between the aggregate types evaluated. ▪ The LFWD results displayed mixed trends between aggregate types, where the LFWD was able to capture the change in modulus with moisture content for some natural sand and dense graded aggregates but not for reclaimed concrete aggregates. It was hypothesized that the mould size influenced LFWD results. ▪ The DCP was the most suitable device for capturing the change in moisture contents within samples while the LWD and BCD showed mixed trends. Specifically, 2% above and below the OMC. ▪ DCP prediction model was found to be adequate at predicting laboratory and field DCP measurements. The model was also found be significantly dependent on moisture content, % passing 4.75 and 0.075 mm sieve. ▪ The DCP prediction model was successfully used for identifying a set of recommended DCP penetration rates that would ensure satisfactory compaction. ▪ A set of specifications for using the DCP as a compaction acceptance tool for natural soils and engineered aggregates was successfully developed.
Lee, Lacey and Look (2017)	▪ NDM ▪ Sand replacement test	▪ DCP ▪ PANDA probe ▪ Plate load test ▪ LFWD (Prima 100) ▪ LFWD (Zorn) ▪ Clegg Hammer ▪ GeoGauge ▪ Borehole shear tester	▪ Cohesive ▪ Sand ▪ Gravel	▪ The study involved conducting a comprehensive review of literature regarding alternative QA methods for earthworks and pavement materials, compiling both Australian and international literature. ▪ The review resulted in a ranking of the alternative methods based upon the accuracy, repeatability, and reliability of equipment (30%), requirement/duration/ease of processing the results (25%), duration of test (20%), operating cost (15%), principal (purchasing) cost (10%). ▪ Weightings from highest to lowest were LFWD (Prima 100) (82%), GeoGauge (79%), LFWD (Zorn) (78%), Clegg Hammer (78%), PANDA probe (74%), borehole shear tester (66%), DCP (58%) and plate load test (52%). ▪ The LFWD has been used as a QA tool by TMR for the compaction of gravel-dominated material with a comparatively large particle size. ▪ The testing speed and measurement depths of the DCP, PANDA, plate load test, LFWD and Clegg Hammer exceed that of the sand replacement and NDM. ▪ TMR has used the LFWD to characterise residual soil and weak rock materials where density and penetration testing would be unsuitable. ▪ Comparative studies in Queensland between the plate load tester and the LFWD have identified the potential for LFWDs to be used as a QA technique.
Weber (2018)	▪ NDM ▪ Sand cone ▪ Rubber balloon	▪ MDI ▪ EDG ▪ SDG ▪ Clegg Hammer ▪ GeoGauge ▪ LFWD ▪ DCP	▪ Granular materials (35% or less passing 0.075 mm sieve)	▪ The study was conducted through literature review, a survey of four US state road agencies and data analysis provided by the South Dakota Department of Transport (SDDOT). ▪ Literature review indicated that all alternative methods had issues obtaining quick, repeatable, reliable and accurate test results. The Clegg Hammer, GeoGauge, LFWD and DCP were found to have quicker testing times and required less expertise to operate. ▪ The most desirable alternatives based on cost, ease of use, repeatability, reliability, accuracy, safety, test time, correlations and required expertise level were the DCP (11), LFWD (13), Clegg Hammer (19), GeoGauge (21), SDG (22), MDI (22), EDG (23). For comparison, the NDM (17), sand cone (19) and rubber balloon (21). ▪ Analysis of survey and data analysis results indicated that the DCP may be a suitable alternative to the NDM for field compaction quality control. ▪ Two methods were presented for compaction control, a method for determining adequate compaction of base and subbase granular materials with a maximum particle size less than or equal to 38 mm. The second method is for recycled materials with a maximum particle size less than or equal to 38 mm.

Table A 2: Alternative density test method evaluation

Category	QA method	Advantages	Disadvantages	Assessment of use as a QA tool	Issues
Volume replacement method	Steel shot	▪ Quick and economical. ▪ Simple, self-contained, does not require calibration. ▪ Requires little training.	▪ Not widely used. ▪ Destructive. ▪ Accuracy and precision of results shows significant variability, indicating that it is unsuitable for QA.	▪ Berney, Meijias-Santiago and Kyzar (2013) found that the steel shot showed significant variability and was unsuitable for use as a QA tool, although it may be useful for low logistic efforts where only rough measures of density are required. ▪ Berney and Kyzar (2012) found that the steel shot results had significant variability and was not suitable for QA.	▪ Simplification of the sand cone method sacrificing accuracy and precision for time.
Penetration test	Dynamic cone penetrometer (DCP)	▪ Quick and economical (10 min/test). ▪ Simple, self-contained, does not require calibration. ▪ Requires little training. ▪ Widely used, standard specifications and test methods available. ▪ High strength correlations with strength and stiffness properties when applied to uniform materials.	▪ Does not directly measure a strength or material parameter. ▪ Conversions between DCP blow count and material parameters are dependent on soil type – site specific correlations with other test methods are typically required for maximum accuracy. ▪ Insensitive tool – comparative tip movement per blow not consistently monitored after each hammer blow, hammer imparted energy is not measured. ▪ Test repeatability can have large spread and be unsuitable for target compaction thresholds. ▪ Unsuitable for granular unbound materials (>50 mm).	▪ Abyad (2016), Mehta and Ali (2016) found it could replace NDM. ▪ Berney, Meijias-Santiago and Kyzar (2013) indicated it may be an NDM alternative if correlations relating blows to density are developed. ▪ Lee, Lacey and Look (2017) indicated that it may be a valuable profiling tool to identify comparative changes in strength with depth.	▪ Penetration increases with moisture content. ▪ Penetration decrease as dry density increases. ▪ Unsuitable for granular/large materials. ▪ Penetration increases with plasticity.
	PANDA probe	▪ Quick and economical (10 min/test). ▪ Simple, self-contained, does not require calibration. ▪ Requires little training. ▪ Hammer imparted energy is measured. ▪ Comparative tip movement per blow is consistently monitored. ▪ High strength correlations with strength and stiffness properties.	▪ Not widely used. ▪ Does not directly measure a strength or material parameter. ▪ Site specific correlations with material parameter required for maximum accuracy. ▪ Unsuitable for granular unbound materials.	▪ Lee, Lacey and Look (2017) indicated it may have greater repeatability and sensitivity to in situ density than DCP. Valuable profiling tool. ▪ Rathje et al. (2006) found that the PANDA is best suited for profiling compaction over a depth of several feet and does not provide accurate estimates of compaction for the top few inches. Therefore, not suitable for lifts less than 150 mm.	▪ Penetration increases with moisture content. ▪ Penetration decrease as dry density increases. ▪ Unsuitable for granular/large materials. ▪ Penetration increases with plasticity. ▪ Based on French system not the Unified Soil Classification System (USCS), as such it is difficult for operators (Rathje et al. 2006).
	Borehole shear tester	▪ Direct measurement of in situ parameters. ▪ Minimises soil disturbance. ▪ Quick and economical (20 min/test). ▪ Simple, self-contained, does not require calibration. ▪ Allows spatial profiling to be undertaken.	▪ No standard specifications available. ▪ Soil pore water pressure and matric suction may affect results and accuracy. ▪ Large particles can impact shear strength measurements.	▪ Lee, Lacey and Look (2017) found that this method evaluates the Mohr-Coulomb strength parameters in-stu. Potential for use with high embankments.	▪ Requires borehole to complete. ▪ Testing of dry non-cohesive materials is difficult.
Surface-based impact devices	Static plate load test	▪ Direct measurement of site/material deformation response to applied load. ▪ Load magnitude can be adjusted to represent design load. ▪ Reference method for field measurement of deformation (modulus) parameter. ▪ Accepted by regulatory authorities.	▪ Slow, each test takes (1 hour/test). ▪ Comparatively expensive. ▪ Requires a large external force. ▪ Cannot be completed in narrow trenches/test pits.	▪ Lee, Lacey and Look (2017) accepted by regulatory authorities but disadvantages stop widespread adoption.	▪ Duration of test.
	Light Falling Weight Deflectometer (LFWD)	▪ Direct measurement of site/material deformation response to applied load. ▪ Portable, self-contained and small test footprint. ▪ Quick (5 min/test). ▪ Repeatable.	▪ Load modulus must be correlated to reference modulus parameter to account for stress/strain variation between test and permanent conditions. ▪ Needs to be calibrated to a standardised test stress. ▪ Different brands/configurations can produce varying results. ▪ Results only represent material at test moisture conditions. ▪ Depth of test limited to 1.33–1.5 times the plate diameter.	▪ Berney, Meijias-Santiago and Kyzar (2013) LFWD readings do not correlate with NDM moisture and density values. With correlations it may be an alternative. ▪ Nebraska Transportation Center (2011) indicated that LFWD may have similar or better accuracy than NDM with improved methodology to create soil models. ▪ Abyad (2016) not influenced by changes in sample moisture content for natural sand and reclaimed concrete aggregates. ▪ Mehta and Ali (2016) results showed mixed trends at 2% above and below soil OMC ▪ Weber (2018) desirable alternative. ▪ Lee, Lacey and Look (2018) found that within Australia it has significant potential as a compaction QA tool. The LFWD has been used as a QA tool by TMR for the compaction of gravel-dominated material with a comparatively large particle size.	▪ Limited by correlations of relating readings to measured density.

Category	QA method	Advantages	Disadvantages	Assessment of use as a QA tool	Issues
	Clegg Hammer	▪ Easy to operate. ▪ CBR correlations are available. ▪ Quick (5 min/test).	▪ Not a modulus testing device. ▪ Does not measure moisture content.	▪ Rathje et al. (2006) provides general assessment of compaction dry unit weight but not the precision for QA. ▪ Berney, Meijias-Santiago and Kyzar (2013) readings do not correlate with NDM moisture and density values. With correlations it may be an alternative. ▪ Weber (2018) third most desirable alternative.	▪ Limited by correlations of relating readings to measured density as the device does not directly measure stress.
	Briaud compaction device (BCD)	▪ Quick (5 seconds/test). ▪ Target modulus threshold and modulus vs. moisture content curve can be determined in laboratory and directly transferred to field testing. ▪ Direct measurement of site/material deformation response to applied load. ▪ Portable, self-contained and small test footprint. ▪ Repeatable.	▪ Stress/strain level of test is not representative of foundation or traffic loading, making it incompatible for direct use in design. ▪ Not suitable for materials with a modulus outside of the range (5 MPa < E < 150 MPa). ▪ Variable test results. ▪ Reported parameter is dependent on operator interaction with equipment.	▪ Abyad (2016) found BCD is sensitive to changes in moisture content and results were highly variable. Not capable of capturing differences in compaction efforts although the device is sensitive to aggregate type.	▪ Placement and execution of test must be near perfect for accurate results (Abyad 2016). ▪ When utilised on very soft soils, the weight of the device may cause the strain plate to sink, affecting results (Abyad 2016).
	GeoGauge	▪ Direct measurement of site/material deformation response to applied load. ▪ Portable, self-contained and small test footprint. ▪ Quick (1–2 minutes/test).	▪ Stress/strain level of test is not representative of foundation or traffic loading, making it incompatible for direct use in design. ▪ Resultant stiffness parameter is sensitive to moisture content. ▪ Method is sensitive to shrinkage cracks and material voids and is not applicable to aggregate or granular material containing less than 20% fines. ▪ Results can be affected by construction traffic in the vicinity of the test location.	▪ Idaho Transportation Department (2015) showed no consistent correlation with density and moisture values from the sand cone or NDM. ▪ Berney, Meijias-Santiago and Kyzar (2013) readings do not correlate with NDM moisture and density values. With correlations it may be an alternative to NDM.	▪ Limited by correlations of relating readings to measured density. ▪ Issues with test fine grained soils with high moisture contents and dry sands. ▪ Uses small strain stiffness.
Electrical moisture-density devices	Moisture and density indicator (MDI)	▪ Completely non-intrusive test. ▪ Can determine the density and moisture content of the soil.	▪ Complex and time consuming testing and calibration procedure. ▪ Cannot test high plasticity clay.	▪ Rathje et al. (2006) issues with clayey soils and sandy soils. ▪ Berney, Meijias-Santiago and Kyzar (2013) highly prone to error, showing errors for approximately 30% across all soils tested. ▪ Vermont Agency of Transportation (2007) exhibited a linear relationship R-value of 0.90, however, the results showed consistently lower in-place dry density readings compared to the NDM. Although the moisture content relationship did not show a favourable comparison with fine or coarse grained soils.	▪ The force required to break the guide plate loose from the probes while in the soil may result in loosening of pins in the soil (Vermont Agency of Transportation 2007; Berney, Meijias-Santiago and Kyzar 2013).
	Electrical density gauge (EDG)	▪ Completely non-intrusive test. ▪ Can determine the density and moisture content of the soil.	▪ Complex and time consuming testing and calibration procedure. ▪ NDM is required for calibration. ▪ Cannot test high plasticity clays.	▪ Idaho Transportation Department (2015) found that the EDG showed poor correlation with the sand cone densities for all soil types. Relative to the NDM, results showed good correlation with sand, fair correlation with granular and poor correlation with fine-grained soils. Although results were positive, not ready to replace NDM. ▪ Nebraska Transportation Center (2011) raw results were similar to NDM, although the NDM performed better when correction factors were applied. ▪ Berney, Meijias-Santiago and Kyzar (2013) had the best precision but only average accuracy compared to the NDM. ▪ Vermont Agency of Transportation (2007) found that it compared well with the NDM, especially with fine grained materials, showing a linear relationship R-value of 0.90. However, it did not show a favourable moisture comparison trend with either coarse or fine grained soil.	▪ No current methods to improve the EDG raw data (Nebraska Transportation Center 2011). ▪ The accuracy and precision is dependent on proper calibration points which is complex, resulting in greater measurement variability (Berney & Kyzar 2012; Berney, Meijias-Santiago & Kyzar 2013).
	Soil density gauge (SDG)	▪ Completely non-intrusive test. ▪ Can determine the density and moisture content of the soil.	▪ Requires extensive operator training.	▪ Idaho Transportation Department (2015), relative to the NDM, results showed good moisture correlation with granular but poor correlation with fine-grained soils and sands. ▪ Berney, Meijias-Santiago and Kyzar (2013) found that the SDG had a good measure of accuracy but lacks precision. ▪ Berney and Kyzar (2012) found that the corrected SDG values showed the least variability in average density over a range of soil types, indicating that it may be the best substitute for the NDM. However, uncorrected values showed considerably more variability, indicating a lack of sufficient internal calibration for the soils tested.	▪ Accuracy is highly dependent upon proper calibration with PSD and Atterberg limits. Must also be calibrated to an average of 2–3 density measurements using a traditional device (Berney, Meijias-Santiago & Kyzar 2013).

Category	QA method	Advantages	Disadvantages	Assessment of use as a QA tool	Issues
Geophysical methods	Portable seismic pavement analyser (PSPA)	▪ Can be compared with laboratory measurements. ▪ The device allows the separate measurement of soil properties for multiple layers. ▪ Not influenced by aggregate type.	▪ Test can be time consuming. ▪ Complex data processing. ▪ May be affected by the surrounding geometry.	▪ Rathje et al. (2006) indicates that PSPA provides a general assessment of the compaction dry unit weight but does not provide the precision required for QA.	

Source: Adapted from Lee, Lacey and Look (2017).

APPENDIX B LITERATURE REVIEW: ALTERNATIVE DRY-BACK METHODS

Table B 1: literature review summary: alternative dry-back test method

Study	Traditional test methods	Alternative methods evaluated	Soils evaluated	Findings
Rathje et al. (2006)	▪ Convection oven ▪ Microwave oven ▪ NDM	▪ MDI ▪ EDG ▪ SQI	▪ High-plasticity clay (CH) ▪ Low-plasticity clay (CL) ▪ Well-graded sand (SW) TxDOT type B ▪ Poorly-graded gravel (GP) TxDOT type A ▪ Poorly-graded gravel (GP) TxDOT type D	▪ Research was conducted using a field evaluation study of a number of non-nuclear methods for compaction control across five soil types in the USA. ▪ The MDI showed good agreement with the microwave oven measurements of moisture content in the laboratory. However, in the field, moisture content measurements did not agree with the NDM or either oven drying methods. The MDI measurements of water content in the CH soil were all smaller than the water contents measured by the NDM and oven drying. In the CL soil, the water content values measured by the MDI were larger than the water content values from the NDM and oven drying. MDI water contents for the sandy clay were significantly different than the water content values obtained from the NDM and oven drying. ▪ The EDG has a complex calibration procedure and consistently displayed inaccurate moisture content readings for all soil types in the laboratory. Field testing was not conducted with the EDG as it could not be field calibrated. ▪ SQI appears to have a good theoretical basis for relating electrical soil properties to dry unit weight and if the manufacturer can develop a robust calibration procedure, the device may be useful in the future. It was not used for laboratory or field testing in this study.
Vermont Agency of Transportation (2007)	▪ NDM	▪ MDI ▪ EDG	▪ Subbase gravel ▪ Granular backfill ▪ Sand borrow ▪ Crusher run	▪ Two electrical devices were compared to the NDM using field testing in the USA. ▪ The moisture contents relationship had an R-value of 0.29 for EDG and 0.35 for MDI. Neither device showed a favourable comparison trend with the NDM in either a coarse or fine grained material. The moisture density curve was constructed in accordance with AASHTO T99 and T180 using the 4–inch mould provided with the MDI lab kit.
Berney, Kyzar and Oyelam (2011)	▪ Convection oven ▪ Microwave oven ▪ NDM	▪ EDG ▪ SDG ▪ Field microwave oven ▪ Moisture analyser ▪ Open flame gas burner ▪ Speedy moisture tester	▪ Silty-gravel (SM) ▪ Clayey-gravel (SP-SC) ▪ Buckshot clay (CH) ▪ Concrete sand (SP) ▪ Crushed limestone (GP-GM) ▪ Vicksburg loess (ML) ▪ Silty-sand (ML)	▪ Based on laboratory and field testing, the moisture contents of seven soils was tested using both traditional and alternative test methods in the USA. ▪ The laboratory microwave oven can over-dry silt and clay soils, resulting in excessive reported moisture contents. ▪ The NDM was used as a reference and performed better than all the alternative test methods evaluated compared to the convection oven method. ▪ The EDG returned very accurate measures of moisture content was its precision was the worst of all devices tested. Furthermore, calibration was relatively complex. ▪ SDG results were very accurate for all soil types when calibrated using the convection oven, although without calibration the readings were inaccurate. The functionality was the best of the devices, making it the most desirable method. ▪ The field microwave oven had varying accuracy for high moisture content silts and clays. Additionally, without a constant power source the wattage decreases with the battery life, resulting in soils drying out fully before test completion. ▪ The moisture analyser is not able to provide sufficient heat to dry out bound moisture in silts or clays and is only recommended for coarse soils. ▪ The open flame gas burner was the most precise and most accurate device of all the alternative methods tested. ▪ The Speedy moisture tester was the most precise device but the least accurate, overestimating moisture content for all soil types. Least desirable alternative device. ▪ The field microwave oven, moisture analyser and open flame gas burner are destructive tests.
Hanson and Nieber (2013)	▪ Convection oven	▪ DOT600 roadbed water content meter ▪ WP4C dewpoint potentiometer ▪ Button heat pulse sensor (BHPS) ▪ Exudation pressure device	▪ Loam ▪ Silt ▪ Silty/clay	▪ Based on the laboratory and field testing, three soils typically used for subgrade applications in Minnesota were studied using four alternative devices in the USA. ▪ The DOT600 factory calibration overestimated volumetric water content from 5%–15% in a number of tests when compared to moisture contents obtained from the oven dried method for all soils tested. ▪ The WP4C did not accurately measure matric suction for any of the loam, silt or silt/clay soils at suctions below 250 kPa. Published data shows that the matric suction of soils compacted at optimum moisture content is usually in the range of 200–300 kPa. ▪ The BHPS showed a strong correlation between measured temperature rise and water content but in its current configuration is not rigorous enough to withstand field conditions. ▪ The relationship between exudation pressure and optimum moisture content needs to be explored on more soil types before it can be more completely analysed. ▪ The DOT600, WP4C and exudation pressure device are destructive test methods.
Sebesta et al. (2013)	▪ Convection oven ▪ NDM	▪ Microwave oven ▪ Direct heat ▪ Moisture analyser ▪ SDG ▪ EDG ▪ DOT600 roadbed water content meter ▪ Frequency domain reflectometry (FDR)	▪ Crushed stone	▪ Based on the outcomes of literature, state road agency surveys and preliminary lab testing, the microwave oven, direct heat, moisture analyser, NDM, convection oven, SDG, EDG, DOT 600 and FDR were selected for field testing in the USA. ▪ FDR can provide quick, accurate results although the probe must be buried in the material under testing. Issue with influence of material density on proper calibration. ▪ Direct heat test turnaround time exceed two hours in some cases. ▪ The moisture analyser, microwave and direct heat methods all provided unbiased estimates of moisture content for passing the 4.75 mm sieve. ▪ Microwave oven was the only device that found unbiased results in all experiments, with tests generally complete in 10 minutes or less. ▪ The NDM provided unbiased field performance. ▪ In comparison with the oven method, the SDG showed bias based moisture content above and below OMC at vary levels. ▪ The EDG was unbiased in initial tests after calibration but showed fixed bias during field testing. This could be corrected with a linear offset. ▪ For in situ testing, the EDG was evaluated to be the most promising replacement for the NDM based on precision, bias, existing test methods, suitability for compacted and uncompacted materials, test time, zone of influence, cost and field practicality.

Study	Traditional test methods	Alternative methods evaluated	Soils evaluated	Findings
Nazzal (2014)	▪ Convection oven ▪ NDM	▪ MDI ▪ EDG ▪ SDG ▪ Speedy moisture tester ▪ Moisture analyser ▪ Field microwave oven ▪ DOT600 roadbed water content meter ▪ Percometer ▪ Trident moisture meter	▪ Varies, study was primarily literature review	▪ This study involved a comprehensive synthesis and review of literature from a variety of US-based and other international studies relative to the use of non-nuclear methods for compaction control of unbound materials, including in situ moisture measurement. ▪ MDI is a repeatable device that showed accurate moisture content measurements close to those obtained using the oven dry method. Although it cannot be used for highly plastic clays. The probes can be difficult to remove from some soils. Studies showed contrasting results, some with good correlation to the NDM and others with poor correlation. However, it was reported that moisture content measurements for sand were accurate with the properly selected calibration constants. ▪ EDG moisture content measurements in literature show mixed results, some varying measurements and some accurate measurements. Less reliable results with poorly graded sand and cannot be used for high plasticity clays. ▪ SDG moisture content measurements were repeatable and accurate compared to the NDM once linear offsets were made to results, although the device may be better suited to granular soil types. ▪ Speedy moisture tester showed good repeatability but poor accuracy and did not work well with coarse grained soils due to the small (20 g) sample size. ▪ Moisture analyser underestimated the moisture content compared with convection oven method based on limited studies. ▪ Field microwave method is suitable for materials consisting of particles smaller than 4.75 mm, limited studies found that it slightly overestimated moisture content. ▪ DOT600 roadbed water content meter may be able to replace the NDM and sand cone test based on overall performance although it cannot be used to test coarse materials. ▪ Percometer was found to be report highly variable results, especially if the soil surface was rough. ▪ One study found that Trident moisture content measurements had a strong correlation with oven dry results, providing accurate readings. ▪ The field microwave oven, moisture analyser and DOT600 are destructive test methods.

Table B 2: Alternative dry-back test method evaluation

Category	QA method	Assessment of use as a QA tool	Issues / limitations
Traditional	NDM	▪ The NDM does not require calibration to the soil and is simple to use in the field. Showed the closest accuracy to the laboratory oven (Berney et al. 2011). ▪ Accepted QA tool by both Australian and international road agencies.	▪ NDM measurements may be affected by the chemical composition of the soil tested (Nazzal 2014). ▪ Requires calibration with the convection oven method. ▪ Strict safety and operational requirements.
Electrical moisture-density devices	MDI	▪ Results from Rathje et al. (2006) indicated variable moisture results for clays. However, sand moisture content results showed good correlation with laboratory results. ▪ Vermont Agency of Transportation (2007) found moisture readings showed high variability for coarse and fine grained soils. ▪ Moisture results for sand were accurate when properly calibrated (Nazzal 2014).	▪ Issues with coarse and fine grained soils. ▪ Cannot be used for high plasticity clays (Nazzal 2014).
	EDG	▪ Accurate measures of moisture content but variable precision (Berney et al. 2011). ▪ Sebesta et al. (2013) found that the EDG was the most promising NDM replacement.	▪ Complex calibration routine to establish accuracy (Berney & Kyzar 2012). ▪ Results with poorly graded sand were variable and device cannot be used for high plasticity clays (Nazzal 2014).
	SDG	▪ When calibration against the laboratory oven is possible, the results were very accurate (Berney et al. 2011). ▪ Repeatable and accurate results compared to the NDM once linear offsets were made to the results.	▪ Complex calibration routine to establish accuracy (Berney & Kyzar 2012; Sebesta et al. 2013). ▪ Without calibration, results were far from true moisture contents (Berney et al. 2011). ▪ May be better suited to granular soil types.
	Percometer	▪ Highly variable test results (Nazzal 2014).	▪ Inconsistent readings if soil surface was round and voids were not completely filled. ▪ High variability in test results.
	Trident moisture meter	▪ One study found that results had a strong correlation with those obtained using the traditional oven dry method for both compacted and loose soils.	▪ Requires material specific calibration and cannot be used for aggregates with a particle size greater than 25 mm.
Chemical	Speedy moisture tester	▪ Moisture content was overestimated for all soil types, although fine grained soils and non-plastic soils yield more accurate measurements (Berney et al. 2011). ▪ Should only be used as a last resort if no other technique is available (Berney et al. 2011).	▪ Small sample size (20 g) only allows for fine grained soil testing. ▪ Soils with high moisture contents require a multiplier for the conversion charts, increasing error. ▪ Cannot be used for highly plastic clayey soil or coarse-grained soil (Berney et al. 2011).

APPENDIX C PSP METHOD SPECIFICATION

C.1 Case Study Summaries

Table C 1: PSP method specification case study summaries

Project	Construction details	Calibration method	Trial data	Method specification recommendations	PSP blows revised	Ongoing monitoring and recalibration
Armadale Rd. Upgrade	▪ 450 mm thick compacted embankment lifts. ▪ Fill material is yellow, medium grained 'Perth' sand sourced from WA Sands. ▪ Two 15 kL water trucks, one 20–ton smooth drum vibratory roller. ▪ Target compaction –95% MMDD.	▪ Off-site trial calibration of approximately 6000 m^2. ▪ Placement of a 550 mm thick loose lift. ▪ 150 L/m^2 water application rate. ▪ Compaction with 6 passes* of a 20–ton smooth drum vibratory roller.	▪ 3 samples characterised using PSD testing. ▪ NDM and PSP testing at 6 staggered locations after each two passes of the roller until 6 passes were completed. ▪ 2 MMDD tests per 6 NDM tests.	▪ 4 passes of the roller. ▪ 8 blows/300 mm (between 150−450 mm bgl) to achieve 95% MMDD. ▪ 12 blows/300 mm (between 450–750 mm) to achieve 95% MMDD.	▪ 10 blows/300 mm (between 150–450 mm bgl) to achieve 95% MMDD.	▪ New compaction trial undertaken where a change in material source or type occurs. ▪ PSD testing at rate of 1 per 2500 m^2. ▪ Moisture content testing 6/lot or lift. ▪ OMC testing min 2/every third lot or lift. ▪ PSP/NDM correlation testing at a minimum of every third lot or lift. NDM testing carried out to full depth of the lift (between 150–450 mm bgl).
Mitchell Freeway Extension	▪ 300 mm compacted embankment lifts. ▪ Fill material is site-won yellow sand (Perth sands). ▪ One water truck, one CAT140H grader, one 12 t Hamm Smooth Drum Roller set to medium to high vibration (approximately 50 hz) with a 1.89 mm vibration amplitude. ▪ Target compaction –95% MMDD.	▪ Field calibration. ▪ Scarify to a depth of 300 mm. ▪ Wet the surface using multiple passes. ▪ Compact with 6–8 passes of a 12 t vibratory roller travelling at approximately 5 km/h.	▪ 1 PSD test. ▪ NDM, MC and PSP testing at 6 staggered locations after the roller passes were completed for each of the 6 lifts.	▪ 11 blows/300 mm (between 150–450 mm bgl) to achieve 95% MMDD.	▪ 11 blows/300 mm (between 150–450 mm bgl) to achieve 95% MMDD.	▪ NDMs are used to confirm that PSP compaction testing conforms to NDM results every third embankment fill lift.
Northlink 1	▪ 300 mm compacted embankment lifts. ▪ Fill material is site-won grey sand (Perth sands). ▪ One water truck, one 15 t smooth drum roller set to high vibration. ▪ Target compaction –95% MMDD.	▪ Calibration trial (not stated whether off-site or field). ▪ Details of calibration method were not provided.	▪ NDM and PSP testing at 7 staggered locations after the roller passes were completed. ▪ 3 MMDD tests, one initial and 2 after two roller passes.	▪ 4 passes of the watercart to meet OMC. ▪ 8 passes of 15 t roller, minimum 10% overlap. ▪ 6 blows/300 mm (between 150–450 bgl) to achieve 95% MMDD.	▪ 7 blows/300 mm (between 150–450 bgl) to achieve 95% MMDD.	▪ Dry density ratio and PSD tests shall be undertaken at every fifth lot or every 1.5 m in the construction section and include first and last lift. ▪ PSP and NDM testing at every fifth lift to verify the correlation. ▪ If a lot fails when tested by PSP or NDM, lot is reworked and tested using the NDM. If the next 3 consecutive lots tested by NDM are compliant the method specification process may resume.
Nicholson Rd.	▪ 450 mm thick compacted embankment lifts. ▪ Fill material is site-won black Bassendean sands, grey/brown sand (both Perth sands). ▪ One 12 t smooth drum roller set to high oscillation, one 2 t mini roller, one 700 kg plate compactor. ▪ Target compaction –95% MMDD.	▪ Field calibration on two project lots. ▪ Condition to OMC. ▪ Compact with one of: – 8 passes of 12 t roller. – 10 passes of 2 t mini roller. – 12 passes of 700 kg plate compactor.	▪ 3 PSD tests (2 for black sands, for backfill and select fill and 1 for grey/brown sand used for backfill). ▪ NDM, MC and PSP testing at 6 staggered locations for each sand type.	▪ 10 blows/300 mm (between 150–450 bgl) to achieve 96% MMDD.	▪ 9 blows/300 mm (between 150–450 bgl) to achieve 95% MMDD.	▪ The material properties shall be verified at a rate of 1 test per 2500 m^2. ▪ NDM, dry density ratio, MC, OMC, PSD and PSP testing shall be undertaken at the initial lift and at a rate of every fifth lot. ▪ Within intermediate lots, 6 PSPs test per lot.
Esperance Port	▪ 300 mm thick compacted embankment lifts. ▪ Fill material is Perth sands. ▪ One watercart, one smooth drum vibratory roller, one 300 kg DPU plate compactor. ▪ Target compaction – 95% MMDD.	▪ Calibration trial (not stated whether off-site or field). ▪ Water the layer with 3 passes of the watercart. ▪ Compact 300 mm of loose sand with 10 passes of vibratory roller.	▪ PSP testing at 6 locations. ▪ NDM testing at 6 randomly selected location once layer 6 has been placed. ▪ 2 OMC test per 6 NDM tests.	▪ 10 blows/300 mm (between 150 – 450 bgl).	▪ 14 blows/300 mm (between 150−450 bgl) – DPU. ▪ 15 blows/300 mm (between 150−450 bgl) – roller.	▪ PSD, NDM and OMC testing shall be undertaken at a rate of every fifth lot.

Project	Construction details	Calibration method	Trial data	Method specification recommendations	PSP blows revised	Ongoing monitoring and recalibration
Gateway WA	▪ 300 mm and 600 mm thick compacted embankment lifts. ▪ Fill material is white to grey sand, yellow select sand (supplied), Brajkovich sand (supplied) and site-won Plot 1C sand – 300 mm lifts. ▪ Fill material is yellow Perth sand, recycled sand (supplied) and Brajkovich sand (supplied) – 600 mm lifts. ▪ One water truck, one CAT140H grader one 15 t Hamm 3412HT VIO smooth steel drum roller set to high vibration (approx 50 hz) with a 1.89 mm vibration amplitude. ▪ Target compaction – 95% MMDD.	▪ Field calibration of three trial lifts. ▪ Wet surface using multiple passes of a water truck. ▪ Scarify to a depth of 200 mm. ▪ 2 passes of 12 t vibratory roller travelling at approximately 5 km/h.	▪ 2 NDM and MC tests at 300 mm bgl after 2 passes with 1 PSP test adjacent to NDM. ▪ Repeat until negligible density increase.	▪ Full thickness of lift conditioned to OMC. ▪ Minimum of 8 roller passes. ▪ Minimum of 6 hand compactor passes (300 mm lift only). ▪ 300 mm lift: – 8 blows/300 mm – white to grey sand. – 14 blows/300 mm – yellow select sand. – 20 DCP blows/300 mm – Brajkovich sand. – 10 blows/300 mm – Plot 1C sand. ▪ 600 mm lift: – 12 PSP blows/300 mm (150–450 mm) – yellow Perth sand. – 12 PSP blows/300 mm (150–450 mm) – recycled sand. – 15 PSP blows/300 mm (300–600 mm) – Brajkovich sand.	▪ 300 mm lift: – 6 blows/300 mm – white to grey sand. – 15 blows/300 mm – yellow select sand. – 17 DCP blows/300 mm – Brajkovich sand. – Plot 1C not available. ▪ 600 mm lift: – 17 PSP blows/300 mm (150–450 mm) – yellow Perth sand. – 10 PSP blows/300 mm (150–450 mm) – recycled sand. – 14 PSP blows/300 mm (300–600 mm) – Brajkovich sand.	▪ Changes in material type will require a new correlation between NDM and PSP. ▪ NDM must be carried out a minimum of every third lift to confirm correlation with PSP is still valid. ▪ PSP testing at the same frequency per lot as required with the NDM.

*Note: One roller pass defined as up and back.

Table C 2: PSP method specification issues and highlights summaries

Project	Issues	Highlights
Armadale Rd Upgrade	▪ The recommended blows/300 mm calculated in the method specification are lower than those inferred from Figure 4.4. ▪ Blows/300 mm between 450 mm and 750 mm depth are also supplied in order to test the top 150 mm of each previous lift however the method of determining this number is not described.	▪ The calibration uses a separate, dedicated test area. ▪ Several material PSDs are supplied to clearly classify the material for which the calibration was undertaken on for future reference. ▪ Presentation of the calibration data is clear and does not include unnecessary information. ▪ Ongoing PSD testing frequencies are specified to ensure ongoing material conformance. ▪ Ongoing MC and OMC testing frequencies are specified to ensure ongoing conformance. ▪ There are clear instructions for the construction process including water application rate and minimum number of roller passes. ▪ Ongoing nuclear density testing frequencies to ensure ongoing density compliance is documented as every third lot or lift (whichever is more stringent) starting with the initial lot. ▪ In the event of a failed NDM test or a change in material, the calibration is to be re-assessed. ▪ All testing is to be completed before the placement of the next lift. ▪ All test certificates from the calibration are included in addition to photographs.
Mitchell Freeway Extension	▪ The table and graphical representation of the calibration data is confusing and includes irrelevant information. ▪ The recommended blows/300 mm calculated in the method specification are the same as those inferred from Figure 4.7, however, the recommended number of blows is less than what correlation with the original data suggests (12 blows/300 mm). ▪ The graphical representation of the PSP and density ratio used to calculate the recommended 11 blows/300 mm (Figure 4.6) is invalid and is entirely dependent on the chosen axis scales. ▪ There is no ongoing requirement to check material conformity to that used in the calibration trial. ▪ There are no ongoing requirements to check MC and MMDD relationships. ▪ There is no guidance in the event of a fail NDM test or a change in material.	▪ Two PSD test certificates are included in the submission. ▪ The calibration activity is undertaken on a separate test area and covers various embankment lifts. ▪ There are clear instructions for the compaction process including roller passes, vibration requirements and roller speed. ▪ Ongoing nuclear density testing frequencies to ensure ongoing density compliance is documented as every third lift. ▪ All test certificates from the calibration are included.
Northlink 1	▪ No material PSD certificates were included in the submission. ▪ The details of the calibration method were not provided. ▪ The recommended blows/300 mm calculated in the method specification are lower than those inferred from Figure 4.9. ▪ The amount of data points for each successive roller pass were not consistent. ▪ The number of roller passes is poor defined for testing, initial (no passes) field density was in compliance with the required field density.	▪ There are clear recommendations for the compaction process, including roller passes and water truck passes. ▪ There an ongoing requirement to check material conformity with dry density ratio (WA 134.1), and PSD (WA 115.2), undertaken at every fifth lift, or every 1.5m in the section of construction and include the first and last lift. ▪ If a lot fails, the next 3 consecutive lots tested by NDM must be compliant, otherwise the method specification process may not resume.

Project	Issues	Highlights
Nicholson Rd	▪ The contractor combined the density results of two types of sand found on site, black sand and grey/brown sand although the gradings (Table 4.8) indicated that the sands were dissimilar. ▪ The recommended blows/300 mm calculated in the method specification are higher than those inferred from Figure 4.12.	▪ There are ongoing requirements to verify the material properties at a rate of one test per 2500 m^3. ▪ The consistency of results is checked with NDM testing (WA 324.2), dry density ratio (WA 134.1), MC (WA 110.1), OMC (WA 133.1), PSD (WA 115.2) and PSP testing (AS 1289.6.3.3) at the initial lift and at a rate of every fifth lot. Within intermediate lots, PSP testing is completed to ensure consistency of results.
Esperance Port	▪ The PSD certificates for the material were not presented. ▪ Did not state where the calibration method was a field trial or conducted at a separate location. ▪ The method specification does not differentiate between the recommended blows/300 mm for the compaction methods. ▪ The recommended blows/300 mm calculated in the method specification are much lower than those inferred from Figure 4.13 and Figure 4.14.	▪ There are clear instruction for the calibration for both of the compaction methods that may be employed, including water application and minimum number of compactor passes. ▪ There are ongoing requirements to verify the material properties using PSD and OMC testing, in accordance with MRWA Specification 201 at every fifth lift. ▪ Compaction conformance is checked at every fifth layer using NDM testing.
Gateway WA	▪ PSD certificates for each material type were not presented. ▪ The recommended PSP/DCP blows calculated in the method specification are generally different to those of the revised analysis	▪ There is a different number of required PSP/DCP blows determined for each of the types of sand and lift thicknesses. ▪ There are clear instructions for the construction process including passes of the water truck, scarification as well as the roller passes, vibration and speed. ▪ Separate relationships between blows and relative compaction were developed for the 300 mm and 600 mm lift thicknesses. ▪ Changes in material type require a new correlation between NDM and PSP. ▪ Compaction conformance is checked at every third layer using NDM testing.

C.2 PSP Method Specification Submission Checklist

Table C 3: PSP method specification submission checklist

Item no.	Item	Required information checklist
1.	Project Background	▪ purpose of submission ▪ project details and location ▪ material source and description (i.e. yellow sand, imported) ▪ lift thickness ▪ intended application (i.e. subgrade, select fill for embankments or backfill) ▪ depth (or depths) of investigation (i.e. 150–450 mm, 300–600 mm) ▪ density compliance requirements as per specification ▪ other relevant project information
2.	Anticipated construction method	▪ area of project and volume of material ▪ lift thickness ▪ anticipated water cart passes, speed, watering rate ▪ anticipated roller weight, type and compaction method ▪ other relevant construction information
3.	Material characterisation	▪ anticipated material to be characterised in accordance with MRWA Specification 302 Earthworks (Main Roads Western Australia 2015) ▪ at least two samples shall be tested for each applicable material ▪ characterisation of the material to include: – PSD (WA 115.2) – MC (WA 110.1) – OMC (WA 133.1). ▪ All test certificates of above characterisation tests
4.	Calibration	▪ identification of calibration type (i.e. trial area calibration or field calibration) ▪ location, date, area of trial and layout figure ▪ equipment detail (i.e. plant models, water conditioning, vibration frequency, roller speed and compaction pattern) ▪ lift preparation and sequence (shall match Anticipated Construction Method) ▪ description of roller calibration method (i.e. fixed roller passes followed by density testing of each lift, or testing after each pass for one lift) ▪ sampling locations (i.e. staggered and marked on figure) ▪ Testing frequencies during calibration (i.e. 6 PSP tests per lift, 2 NDM tests per lift, etc.) for each of the following: – PSP – NDM – PSD – MDD/OMC

<table>
<tr><th>Item no.</th><th>Item</th><th>Required information checklist</th></tr>
<tr><td>5.

Cont...</td><td>Calibration data

Cont...</td><td>
▪ NDM and PSP results presented in tabular form allowing the comparison of PSP blows/300 mm to the MDD
▪ results relating to differing soil types (when required) presented in separated tables
▪ results relating to different test depths (when required) (i.e. 150–450 mm, 300–600 mm) presented in separate tables
▪ conformance of the dataset to characteristic density method outlined in ERN8
▪ graphical presentation of data sets
– density ratio on the x-axis
– PSP blows/300 mm on the y-axis
– a linear trend line with a y-axis intercept of 1.0
– y-axis crossing at density compliance requirement
– regression coefficient noted on graph
▪ different materials and test depths included on individual graphs</td></tr>
<tr><td>6.</td><td>Summary of calibration and ongoing monitoring</td><td>
▪ summary of the minimum PSP blows/300 mm required to achieve the target compaction per layer for each material type used on the project
▪ any notable limitations and/or guidelines that shall be followed for construction to be listed (i.e. minimum number of roller passes, depth applicability of PSP penetration values)
▪ inclusion and completion of following table:
<table>
<tr><th>Test requirement</th><th>Minimum Testing Frequency</th><th>Acceptance criteria</th></tr>
<tr><td>PSP (AS 1289.6.3.3)</td><td>□ tests per lot
□ test depth</td><td>□ minimum blows/300 mm for each test depth</td></tr>
<tr><td>Dry density ratio (WA 134.1)</td><td>□ tests per lot
□ test depth</td><td>□ as per density specification requirements</td></tr>
<tr><td>PSD (WA 115.2)</td><td>□ test per lot</td><td>□ as per specification requirements</td></tr>
<tr><td>MC (WA 110.1 or WA 110.2)</td><td>□ tests per lot</td><td>□ as per specification requirements</td></tr>
<tr><td>OMC</td><td>□ tests per lot</td><td>□ as per specification requirements</td></tr>
</table></td></tr>
</table>