Compaction

Leveraging the benefits of an integrated compaction testing approach

Engage. Envision. Excel.

What is Compaction?

Soil Components:

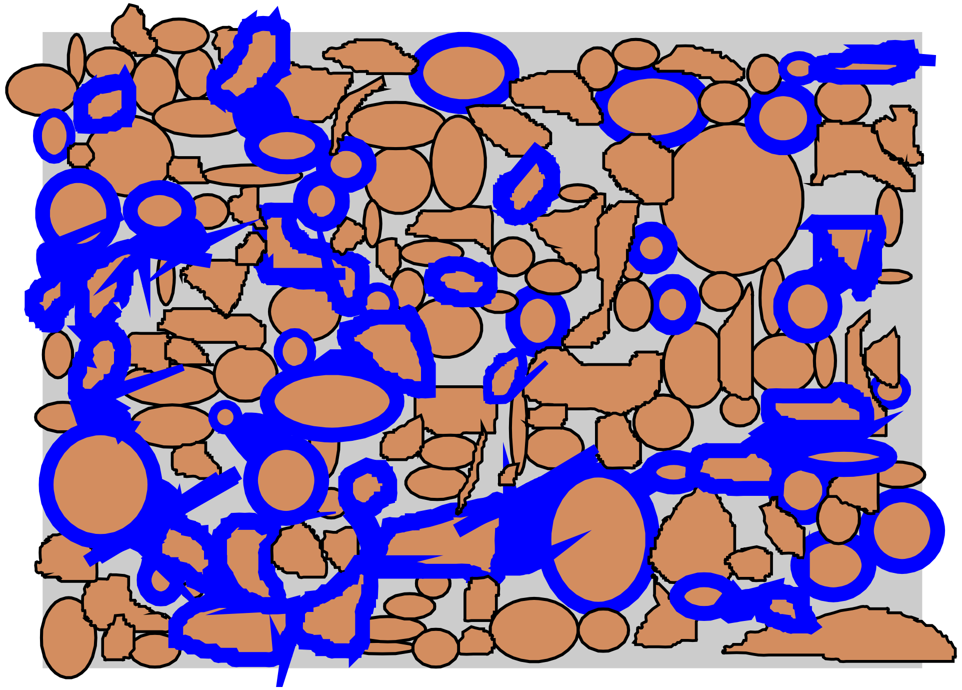
- Mineral Particles
- Water
- Air
- Organic bits (must be removed)

Compaction:

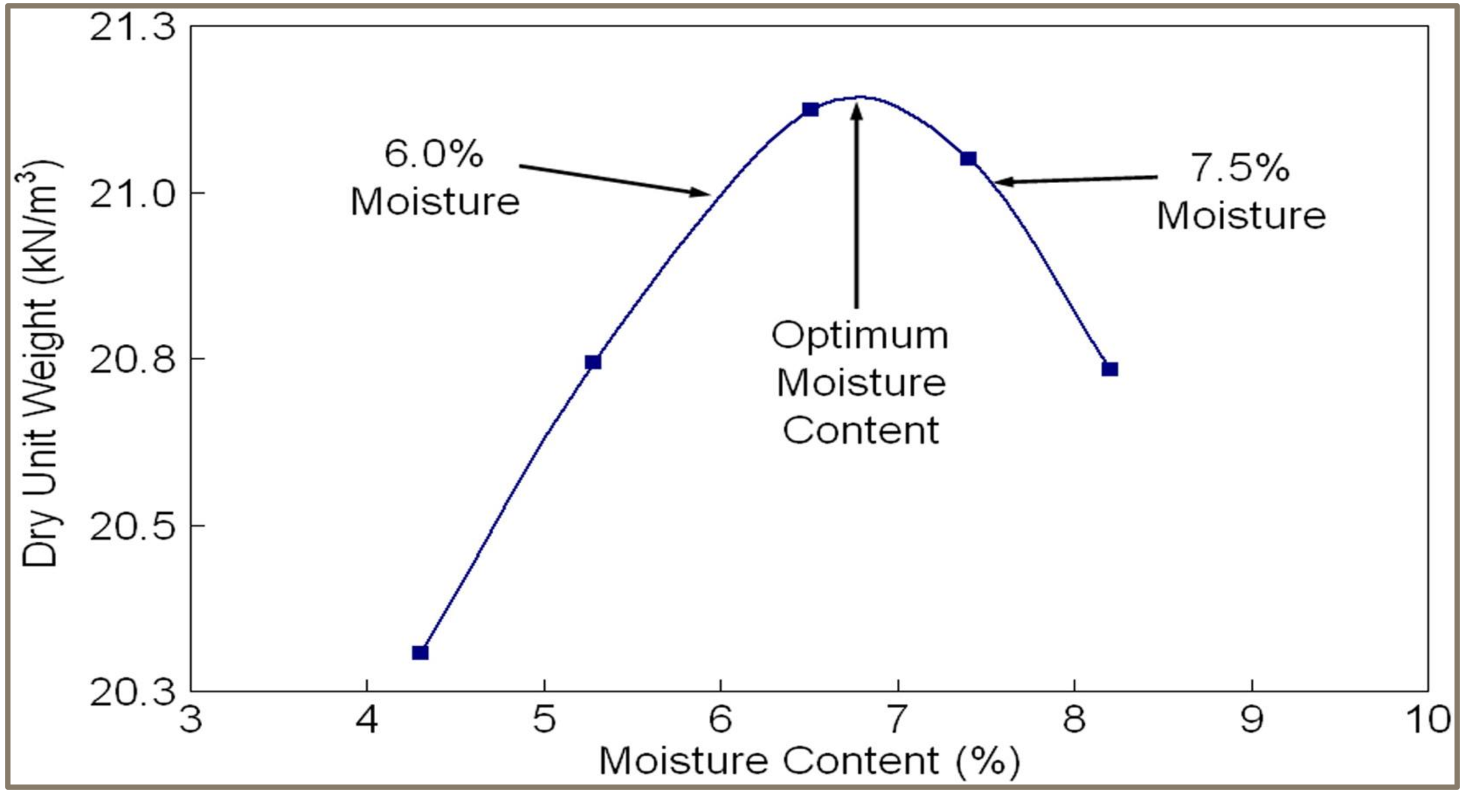
- Reduction of air voids inside the mix
- Mechanical interlocking of particles

Compaction Applications

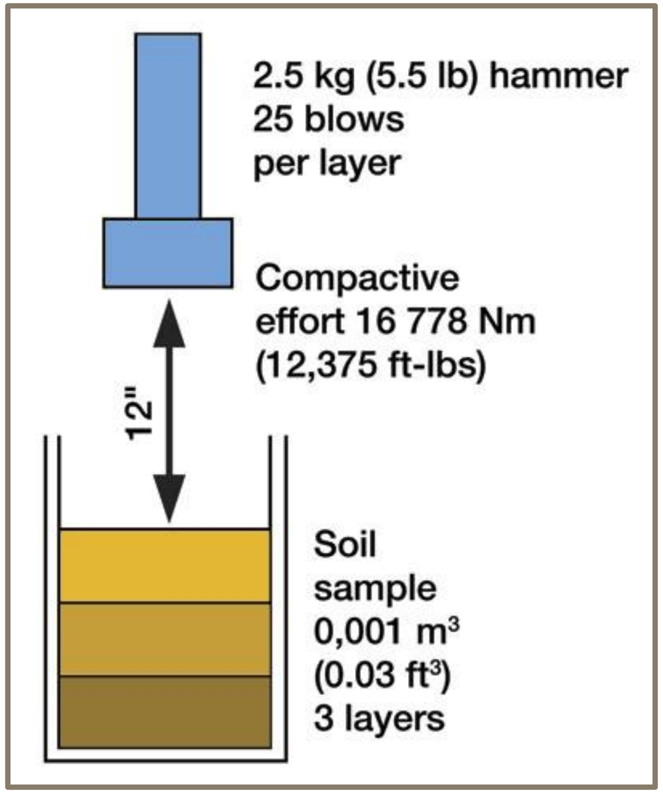
- Bulk earthwork, foundations, backfilling, and pavements



Proctor Compaction Test



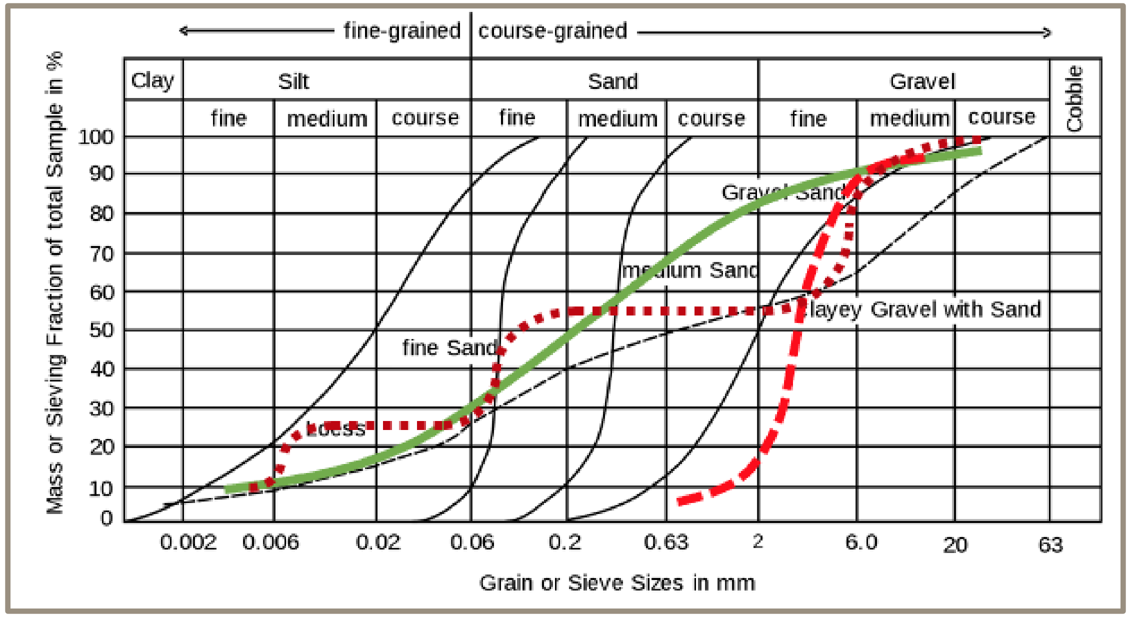
Most commonly used - Mould A – 19mm Max Grain Size



ASTM D698

Particle Size and Distribution

- Particle sizes & mix crucial to soil compaction
- Laboratory procedure “Sieve analysis”: Tower of several sieves, size decreasing from top to bottom
- Particle sizes and distribution define soil class
- Typical curves:
  - Well graded soil: compacts well, sizes well balanced
  - Poorly graded soil: compacts less good, unbalanced size mix
  - Gap gradation: certain sizes missing, compacts less good



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Why is Compaction Important?

- Crucial for the resilience and longevity of infrastructure

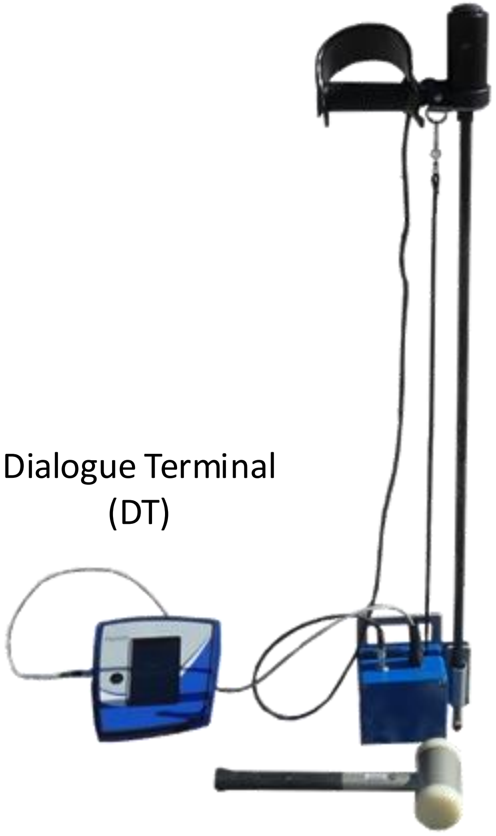
How to Deliver Compaction Better

- Create **uniform** quantified compaction and deliver it as efficiently as possible.
- For best compaction outcomes, combine instrumentation on the compactors and with insitu measurements and real time feedback loops to create an Integrated Compaction Control System.
- Improvements in roller technology and insitu testing methods enable us to compact effectively to deeper depths. e.g. compacting insitu material (e.g. uncontrolled fill layers which may have otherwise been removed and replaced) or compacting material placed in thicker lifts.
- Outcomes: increased productivity, lower costs, improved quality, reduced risk and a reduced environmental impact.

PANDA® Dynamic Cone Penetrometer

Principle:

- Insert a cone
- Variable energy measured
- Depth per blow measured
- Control rod friction
- Granular soils up to 50 mm
- Report cone resistance (qd)
- Soil investigation & compaction control



French Compaction Control Standard NF XP 94-105

PANDA® Versatility Compaction Control/Soil Investigation

- To minimise rod friction, cones larger than the diameter of the rods are used, enabling meaningful data to be collected below the 1-2m limitation of the conventional DCP
- Variable energy means the operator can change the force applied so more data points can be taken, for example, in weak materials.

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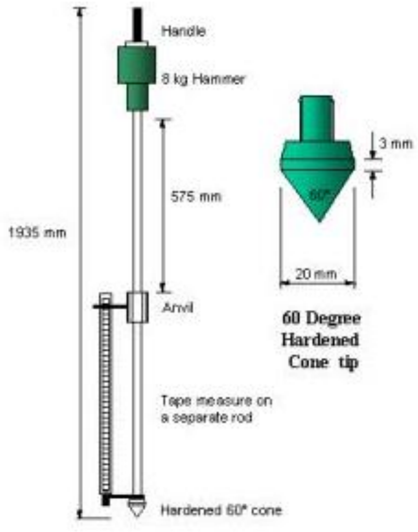
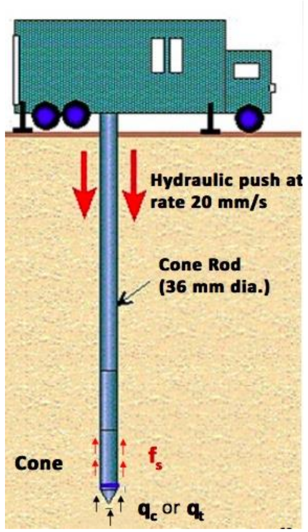
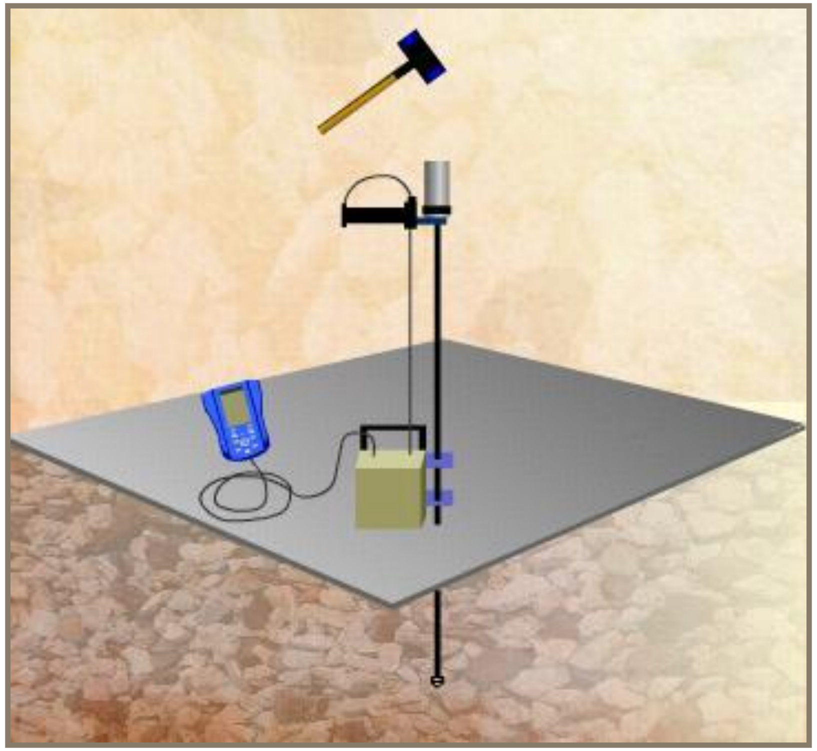
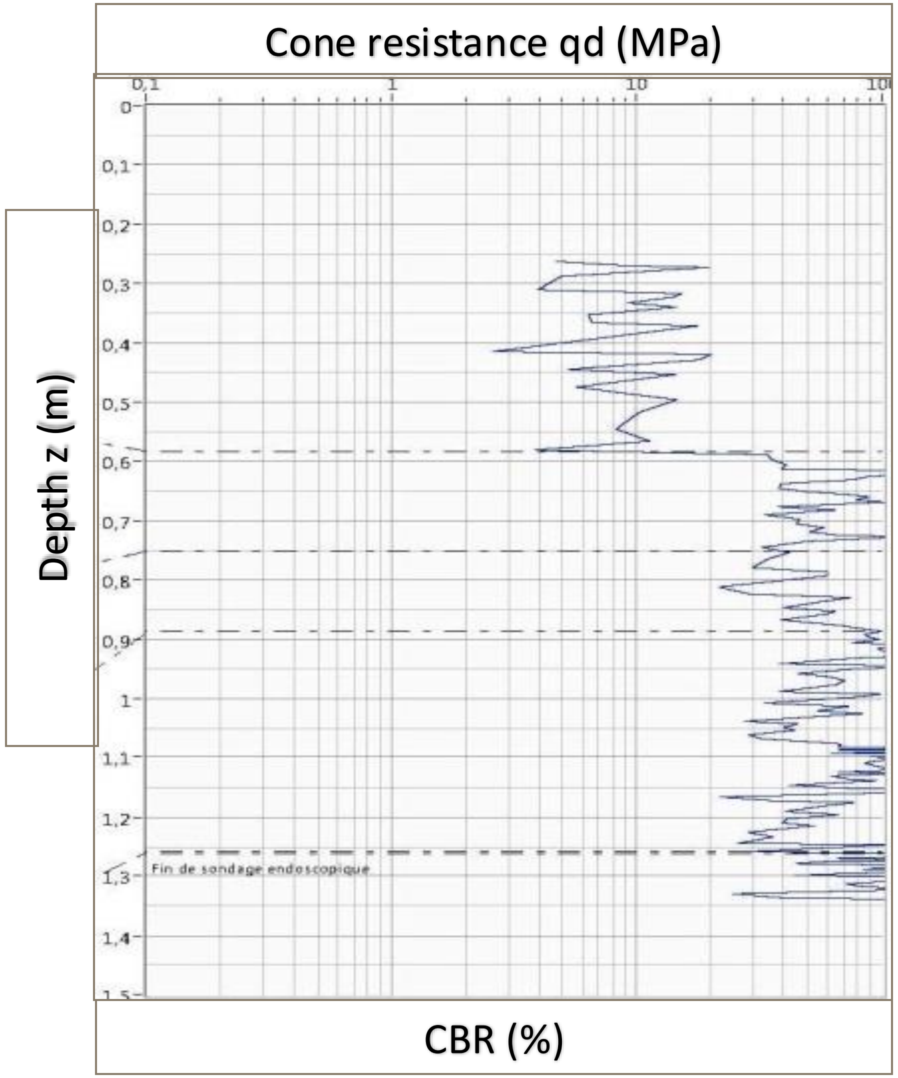
Sophistication Spectrum

Traditional Dynamic Cone Penetrometer (DCP)	PANDA Dynamic Cone Penetrometer (DCP)	Cone Penetration Test (CPT)
		
• Depth per Blow	• Cone tip resistance (q_d) • Sleeve friction (torque wrench)	• Cone tip resistance (q_c or q_t) • Sleeve friction (f_s) • Pore pressure (u) - some

PANDA® Dynamic Cone Penetrometer





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Resistance / Density Relation

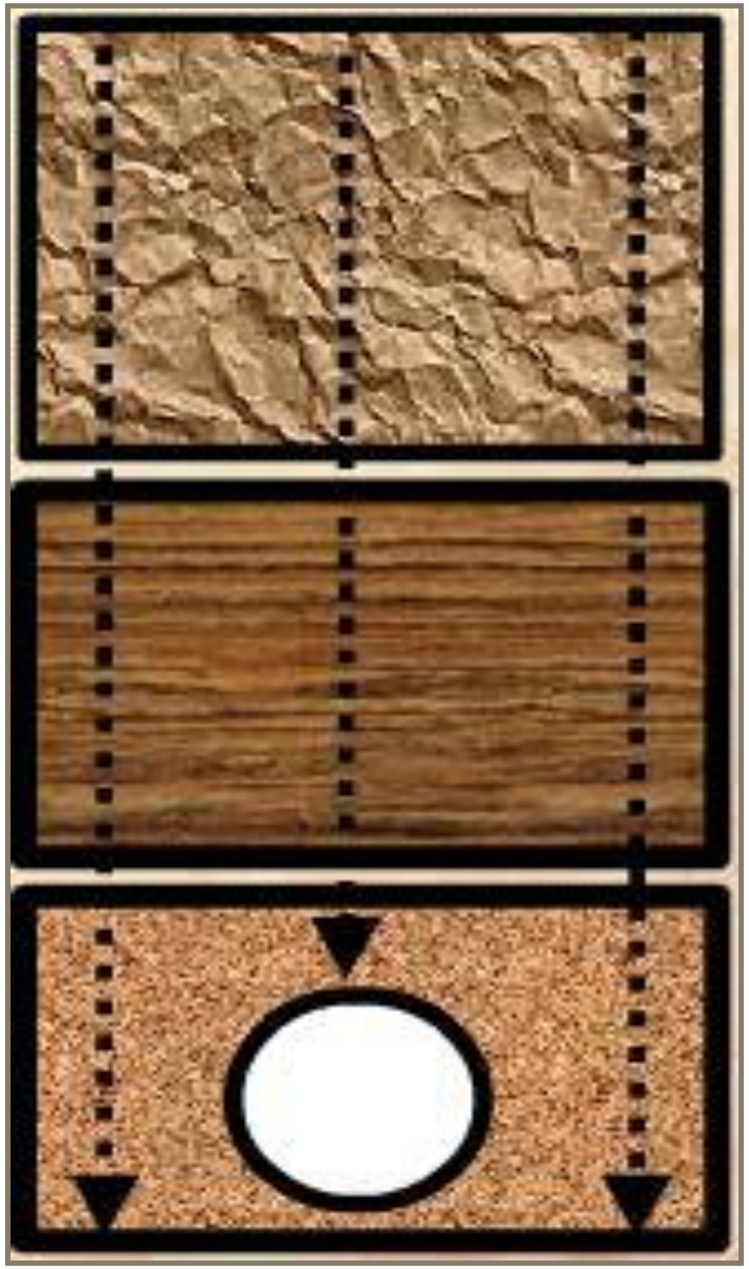
A data bank connecting a range of levels of compaction (% OPN Standard Proctor or Modified Proctor OPM) to the cone penetration resistance (qd) :

- for various soil classifications (AASHTO, USCS, DIN 18196, GTR, etc)
- for hydrous states (dry medium, wet, insensitive)

2cm² fixed cones

Compaction Control Applications

- French Standard: NF XP P 94-105
- Control through the depth of excavation
- Control layer by layer
- Layers' thickness monitoring
- Compaction homogeneity control
- Compaction control of all types of embankment (roads, general earthworks, dam walls, backfill etc)



PANDA® Compaction Control
Database of Soils

- Catalogued in terms of soil classification (plasticity, grain size distribution, water content) and level of compaction
- Over 2,500 data points
- Contains pass/fail qd curves for eighteen natural soil types and three artificial (crushed gravels) soil types.
- Provides target qd curves for two levels of compaction:
    - Standard Proctor (Standard Compaction)
    - Modified Proctor (Modified Compaction)
- For a given soil type and compaction energy, the PANDA® database provides a failure qd curve and a reference qd curve. The region between the two curves is called the tolerance zone.

PANDA® Compaction Control Database Range

Standard Proctor - From 85 to 105 % of the OPN by step of 1%

- When the reference is the Standard Proctor (OPN), the tolerance between the reference green line and the refusal red line is approx. 3% of the OPN
- e.g. 95% OPN for the reference and so 92% OPN for the refusal

Modified Proctor - From 85 to 105 % of the OPM by step of 1%

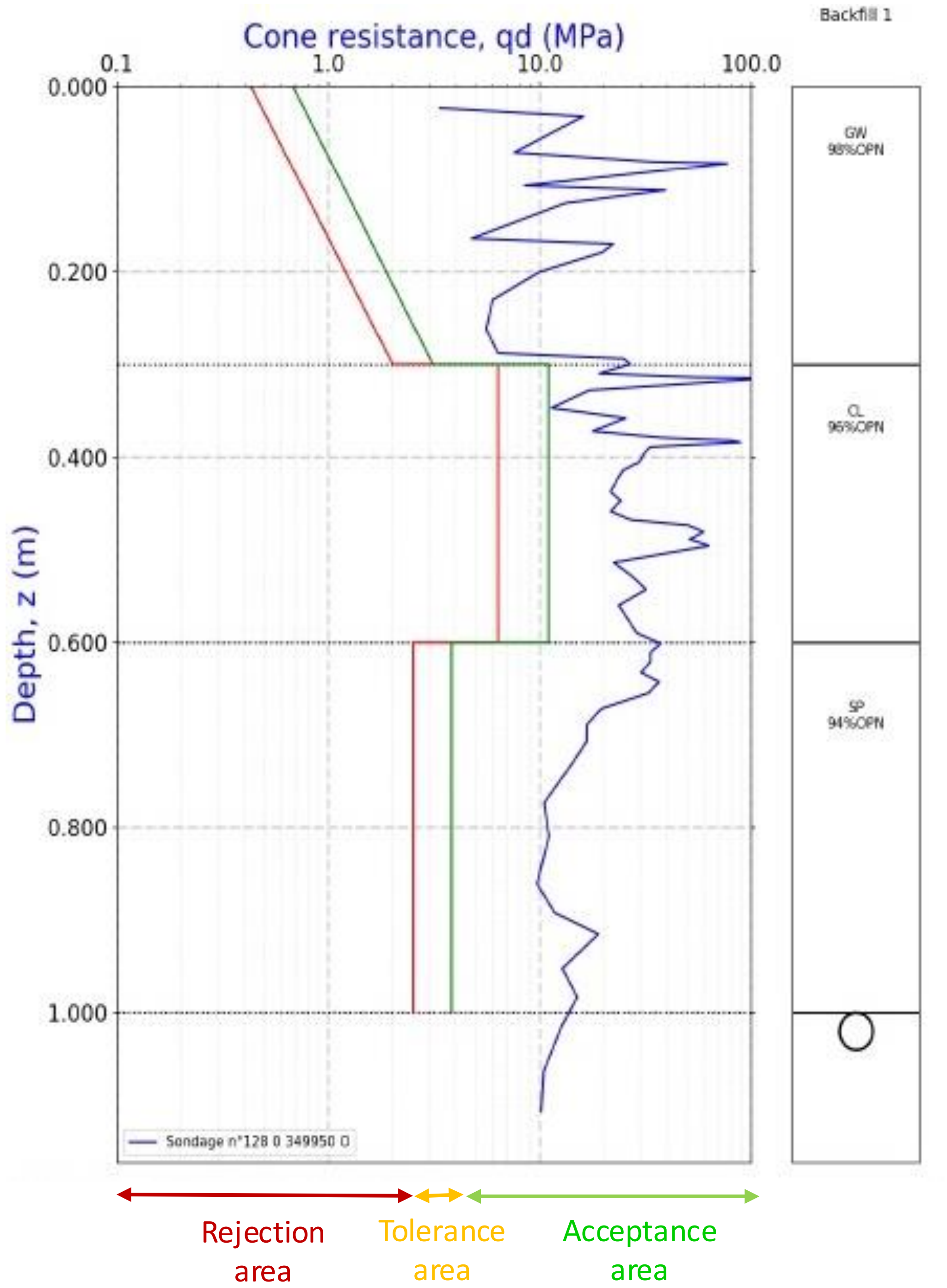
- When the reference is the Modified Proctor (OPM), the tolerance between the reference green line and the refusal red line is approx. 2% of the OPM
- e.g. 95% OPM for the reference and so 93% OPM for the refusal

Compaction Control Typical Output

Interpretation of results

Limit line q_L

Reference line q_R



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Dynamic Probing - DPSH Type B Test Principle

- Hammer a rod and cone into the ground with a drop weight (63.5kg) falling from a fixed height (760mm) (constant energy)
- Measure blows per 10cm or 20cm (as well as depth per blow)

- GRIZZLY adheres to:
  - EN ISO 22476-2 – Geotechnical engineering – Field testing – Part 2: Dynamic probing – DPSH-B
  - NF P94-063 – Compaction quality control – Constant energy dynamic penetrometer method

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GRIZZLY® Profile

- Electronic sensors (depth, blow counter)
- Automatic data acquisition
- Compaction control database
- Integrated software (analysis, anomalies calculation, reporting, correlations)
- Safety controls
- Soil granularity up to 150 mm
- Measures until the target depth
  - Depth per blow (mm/blow)
  - Cone resistance (MPa)
  - N10, N20 and N30
- Variable energy option

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GRIZZLY® Capability

- Soil investigation
  - Variable Energy
- Compaction Control
- Geotechnical Drilling
- Soil Sampling
  - Windowless Push Tube
  - SPT Split Spon
- Powerful 11 tonne hydraulic rod extraction
- GPS location, date & time stamp

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Density versus Stiffness

"Density", "Bearing capacity" & "Stiffness" are NOT equivalent

Density	Bearing capacity	Stiffness (Elasticity) - a material's ability to resist deformation under load:
○ Mass per unit volume (Mass divided by volume) ○ Static, physical material property ○ Popular but vague performance indicator for soil as a construction material	○ Maximum average contact pressure between a foundation and the soil underneath, which should not produce shear failure in the soil ○ Assessment of material behaviour under load (typically static), important criteria for designing building foundations & performance	○ Temporary & reversible material deformation under load (static or dynamic) ○ Strong performance indicator for pavement foundations Pavement performance-based quality control & assurance for compacted soil

Measuring Compaction: Fundamental Changes

From Density to Stiffness

- Stiffness is the basis for calculating an even more fundamental material property, "modulus," which experts agree is the most accurate and independent means for judging deformation and, thus, a material's level of compaction.

* Stiffness is loosely defined as a measure of a material's ability to resist deformation under load

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Compaction Control Approaches

	Traditional	Modern
Design basis	Stiffness / Modulus	Stiffness / Modulus
Measured values (specification)	Density / CBR	Static or Dynamic Modulus
In-situ test methods  DCP / Scala	 Nuclear Density Meter	Plate Load Test   Light Weight Deflectometer

Trailed Falling Weight Deflectometer (FWD)

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Plate Load Test on GeoGrid

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Plate Load Test in a nutshell

- Determine the allowable and ultimate bearing capacity of the ground
- Determine likely settlement under a given load
- By measuring the modulus value, the Plate Load Test provides the link between the design specification (design modulus value) and the actual site condition (in-situ modulus value).

Load cell

Inductive displacement transducer

The load-settlement curve parameters are measured by the sensors.

What Does It Do?

The LWD can be used for:

- measuring deflection
- plotting the Load-settlement (deflection) curve
- calculating Strain moduli of the first and the second loading cycles, Ev1 and Ev2
- calculating the Ratio Ev2/Ev1 (a figure for the degree of compaction)
- calculating the Ratio Ev2/Ev1 (a figure for the degree of compaction)

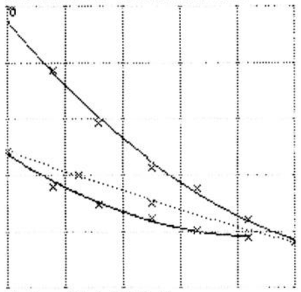
AX01 Plate Load Test

- Fully Instrumented
- Removing the Safety Risks
- Reduces the Test Duration to 30 mins (setup, test and results presented)

PLATE BEARING TEST
DIN 18134-300

Manufacturer: ANIX GmbH
Device no: #4000
Lever ratio: 1:1.00
Plate dia.: 300 mm
Card: #040610164116/1
Date: Fr 04.06.10 16:35
Comments:

s:1.0mm/cm σ:100kN/m²/cm



Ev1 = 29.0 MN/m²
Ev2 = 78.9 MN/m²
Ev2/Ev1 = 2.72

Nr.	σ[MN/m²]	s[mm]
First loading		
0	0.0100	0.00
1	0.0800	1.15
2	0.1600	2.08
3	0.2500	2.87
4	0.3300	3.25
5	0.4200	3.80
6	0.5000	4.21
Unloading		
7	0.2500	3.50
8	0.1250	3.00
Second loading		
9	0.0000	2.59
10	0.0800	3.22
11	0.1600	3.53
12	0.2500	3.78
13	0.3300	3.98
14	0.4200	4.13

Anix GmbH
Precision Electronic Instruments

Test-No.:
Appendix of :

Plate Bearing Test DIN 18134-300

Tester: AX01, Manufacturer: Anix GmbH
Static Plate Bearing Test DIN18134-2001 and TP BF-StB, Teil E1, 1993

Project:
Client:
Weather/Temp.
Prev. day:
Test point:
Test depth:
Layer:
Date: **23.9.03**
Operator:

Record number: 1
Card number.: 230903115428
Start of test: 23.9.03 11:54
End of test: 23.9.03 11:57
Device number: 22
Ø-Plate: 300 mm
Lever ratio: 1:2,00

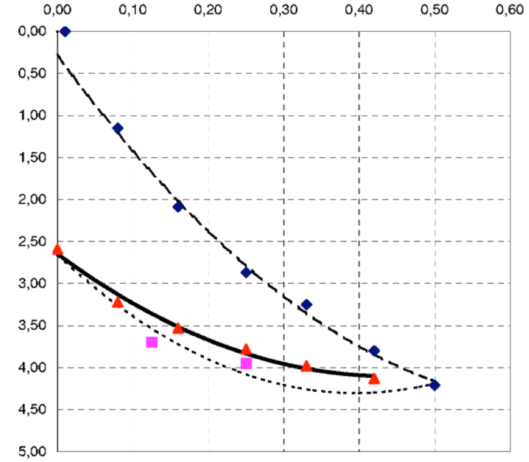
Plate base:
Moisture content below plate:
Stamp, sign:

Results	a_1	a_2	σ_{0max} [MN/m²]	**Actual values**	Nominal values	Rating
Strain modulus E_{v1} [MN/m²]	12,2695	-9,0336	0,5000	**29,0**	≥ 27 *)	Ok.
Strain modulus E_{v2} [MN/m²]	6,6371	-7,5733	0,4200	**78,9**	≥ 45	Ok.
Ratio E_{v2}/E_{v1}				**2,71**	≤ 3,0	Ok.

Remarks:

*) 60% of E_{v2}

Last-stufe	Load σ_o [MN/m²]	Deflection s [mm]
First loading		
1	0,0100	0,00
2	0,0800	1,15
3	0,1600	2,09
4	0,2500	2,87
5	0,3300	3,25
6	0,4200	3,80
7	0,5000	4,21
Unloading		
8	0,2500	3,95
9	0,1250	3,70
Second loading		
10	0,0000	2,59
11	0,0800	3,22
12	0,1600	3,53
13	0,2500	3,78
14	0,3300	3,98
15	0,4200	4,13



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Light Weight Deflectometer Application

- Determine the stiffness of unbound materials (subgrade/subsoils and base layers, granular layers & backfilling materials) or partially bound material (e.g. stabilised) during construction or rehabilitation works

- Rapid layer by layer QC for Compaction on Road, Rail, Tunnels, Runways etc

- Creates link between the design specification (design modulus) and the actual site condition (in-situ modulus value).

Accelerometer based

Light Weight Deflectometer

- It’s repeatable, fast (test is done in 3 minutes) and gives you immediate, GPS located, time stamped results

- The LWD can be used for:
    - measuring deflection
    - determine dynamic modulus
    - assessing the degree of compaction
    - insitu and laboratory dynamic CBR

Example Starter Application

In-situ testing of earthworks during construction, where common techniques (e.g. nuclear gauge/sand replacement) are not appropriate or cost effective

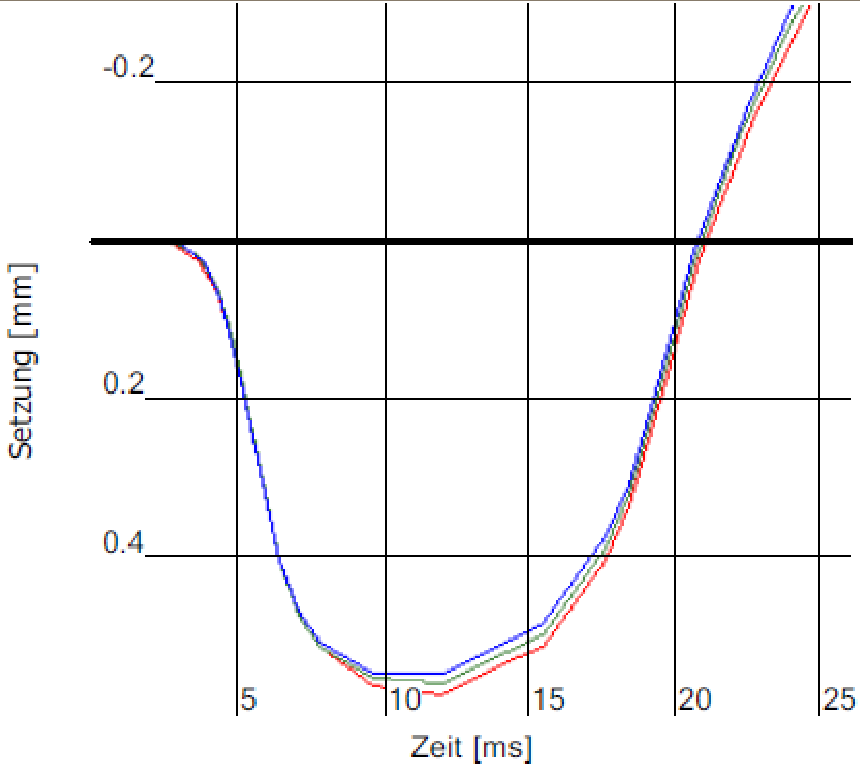
- Fill with larger grain size
- Trenches
- Contaminated sites
- More remote locations

Results and Analysis

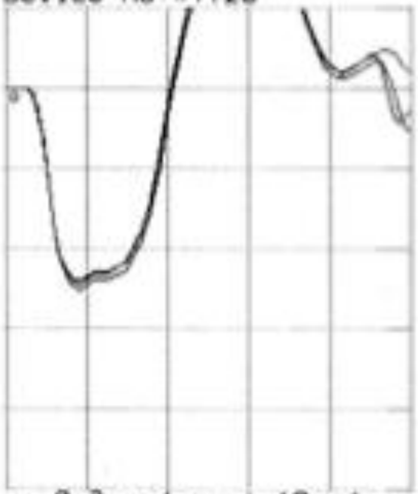
Stoß	v [mm/s]	s [mm]
1	181.9	0.575
2	184.4	0.563
3	183.6	0.554
Ø	183.3	0.564

Ergebnis **Evd: 39.89 MN/m²**

s/v: 3.077ms



DYN. PLATE LOADING TEST
LIGHT DROP-WEIGHT TESTER
TP BF-StB Teil B 8.3
Instrument: ZORN ZFG-3000
Device type: 300mm/10kg
Device no: #4726



s: 0.2 mm/cm t: 10ms/cm
Card: #2104090704591/14
52°49.407' 12°04.382'
Tu 21.04.09 07:23:03

Nr.	v (mm/s)	s (mm)
1.	165.4	0.509
2.	163.2	0.493
3.	163.4	0.487
i.M.	164.0	0.496

s/v= 3.024 ms
Evd= 45.4MN/m²

Weather:

Project:

Plate base:

Testarea, -layer:

Institute, operator:

Draft Technical Note June 2021

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

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AN INITIATIVE BY:

arrb

Queensland Government

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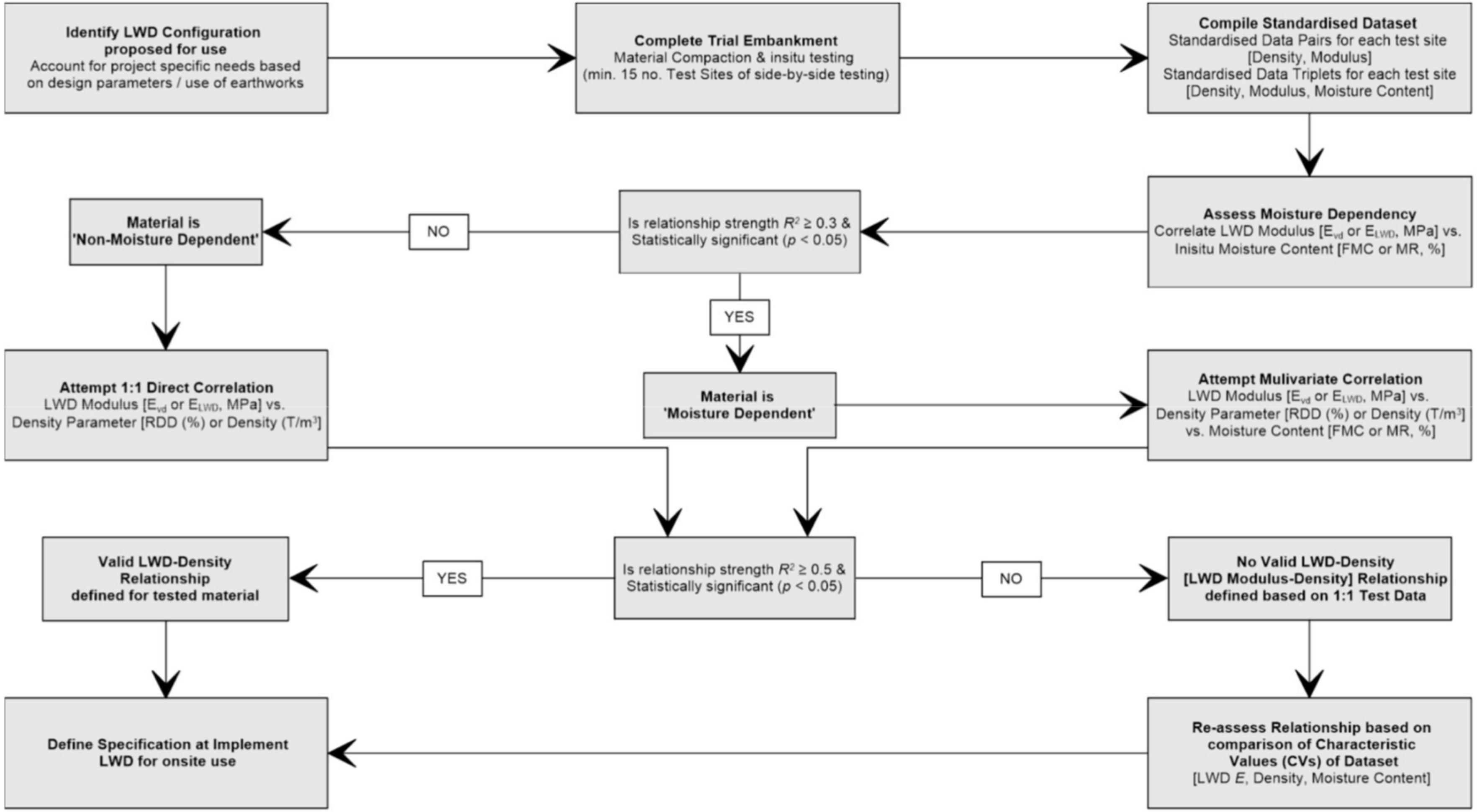


Figure 4 Flow chart showing key steps for assessment/derivation of equivalent acceptance thresholds for LWD use (in lieu of traditional (density) testing minimum thresholds included in MRTS04 – *General Earthworks*)

Intelligent Compaction (IC) /
Continuous Compaction Control (CCC)

Create Uniform Efficient Quantified Compaction

An Integrated Compaction Control System

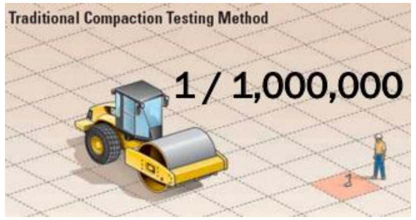
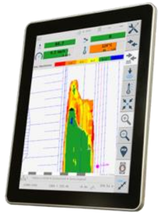
Increase construction productivity, lower cost, improve quality, reduce risk and reduce your environmental footprint

Compaction Approach - Traditional vs Modern

<table>
<tr><th>Design basis</th><th colspan="4">Compaction control</th></tr>
<tr><td></td><td>Compaction method</td><td>Measurement training</td><td>In-situ test methods</td><td>Coverage</td></tr>
<tr><td>Modulus / stiffness</td><td>Traditional method

Operator feel & memory</td><td>Density / CBR

After compaction is complete

Provides little or no “on the fly” feedback</td><td>Nuclear gauge
</td><td>
</td></tr>
<tr><td>Modulus / stiffness</td><td>Modern method
Intelligent compaction
 </td><td>Stiffness / modulus
Ongoing measure & feedback to operator
</td><td>Modulus based (incl. Plate load test & LWD
</td><td>
</td></tr>
</table>

Intelligent Compaction - Soils

Near real time Remote Monitoring

Onboard Reporting

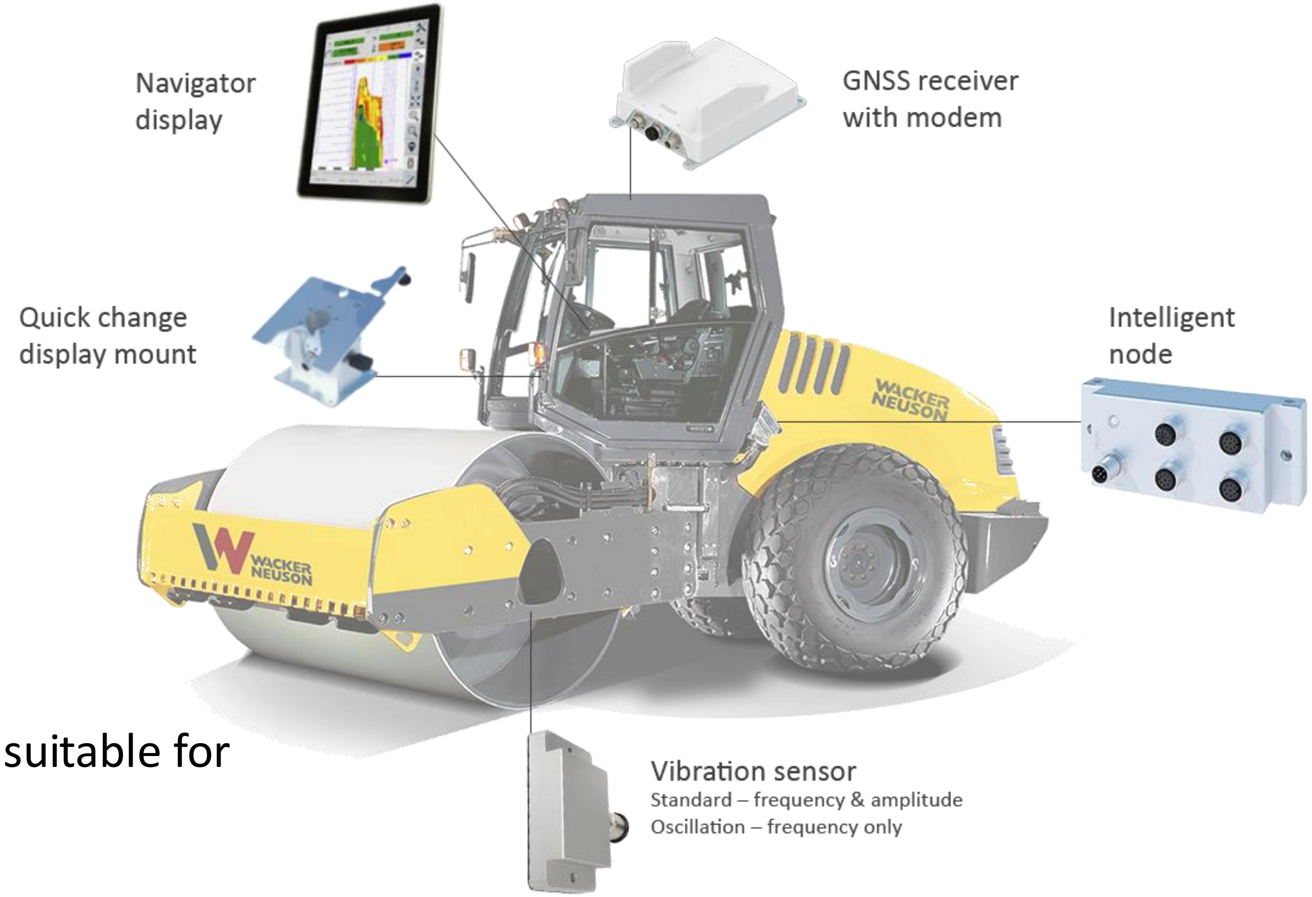
Continuous Measurement

Intelligent Compaction Völkel Kit For Soils

The Terminology Explained

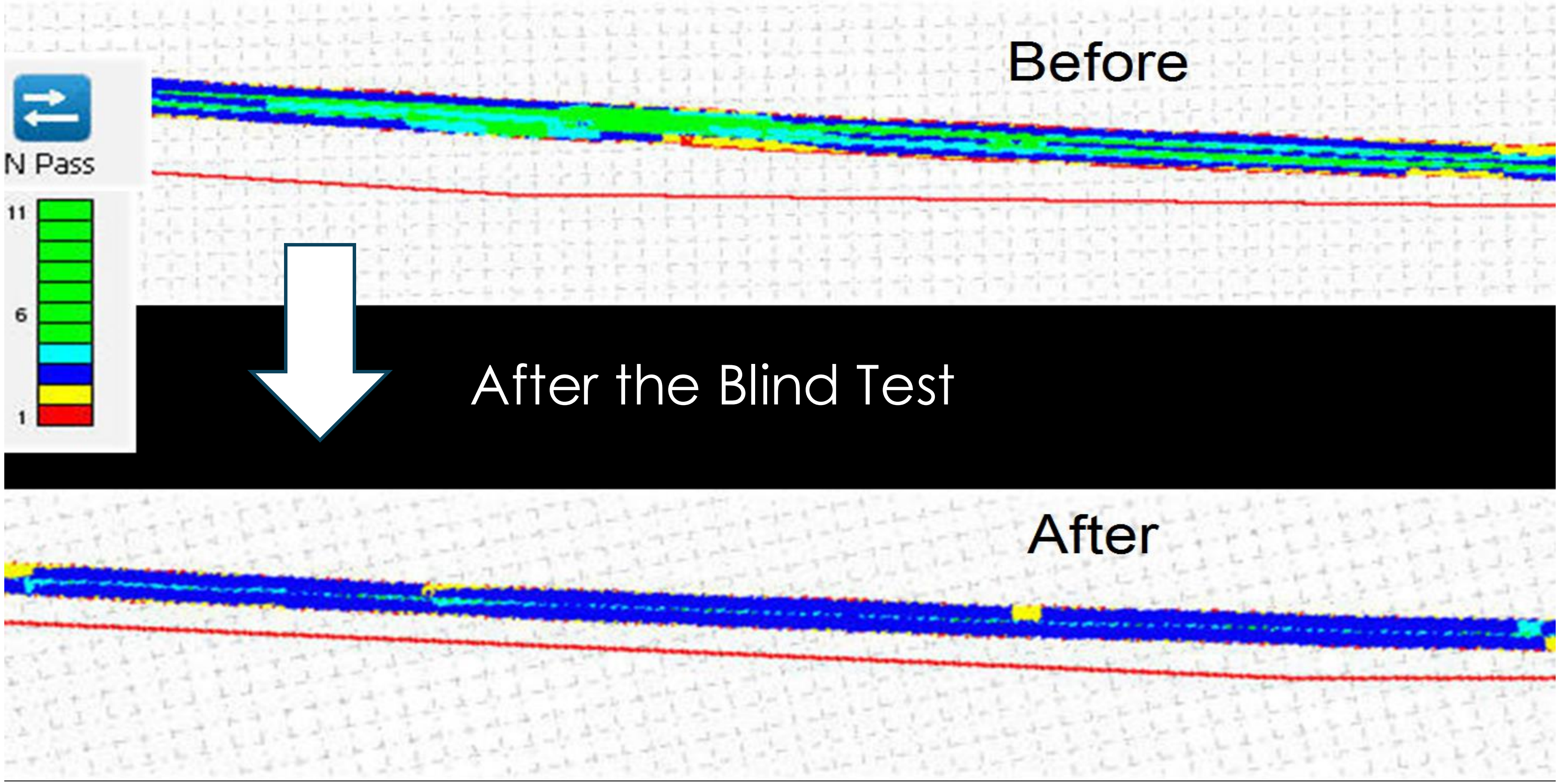
Base installation kit = Intelligent node, quick change display mount, accelerometer sensors and associated wiring

Navigation Kit = Navigator Display and GNSS receiver with modem



Retrofit regardless of manufacturer – suitable for use on most roller types

Improved Rolling Pattern – Blind Test



Kandiyohi County

DEPARTMENT OF TRANSPORTATION

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Quick Win – Pass Count Measurement
Over Rolling, Under Rolling and Gaps

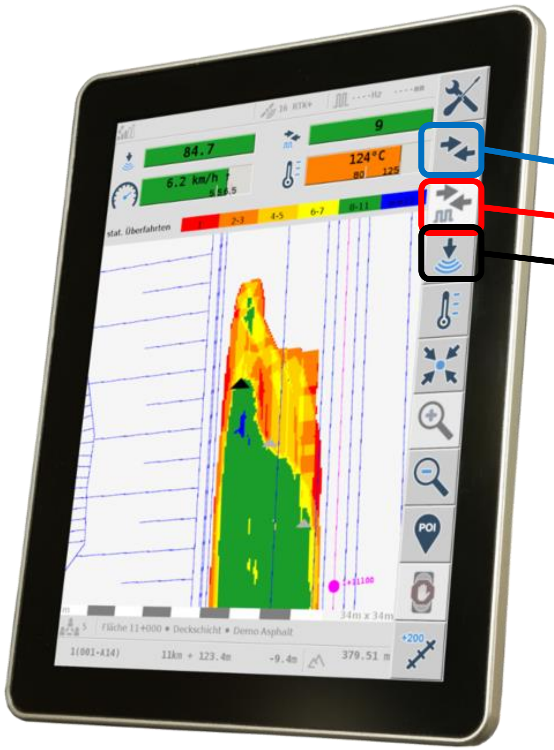
- Eliminate over rolling
  - Commonly leads to ~30% increase in productivity
  - Eliminating increased material usage due to over compaction – importing additional material can be a major unanticipated project cost
- Eliminates under rolling & gaps between passes
- Delivers compaction uniformity
- Time savings (operator & roller hours)
- Less fuel burn
- Lower roller maintenance costs

Pass Count & Coverage Visualisation & Tracking

Precision
Always know actual pass count pass by pass, layer by layer, everywhere on site

Control
Remove manual pass counting pressure and/or mistakes
Synchronisation - All plant operators have the same pass count view
Data isn't lost on shift handover
Chainage integration

Uniformity
Ensure uniform compaction
Roller speed recording



Compliance
Show pass count vs target
Separate map and target each for
- Static pass count
- Dynamic pass count
- Vibration

Clear picture day or night

Efficiency
Commonly leads to ~30% increase in productivity

Skill Development
Accelerates operator proficiency by providing visual feedback

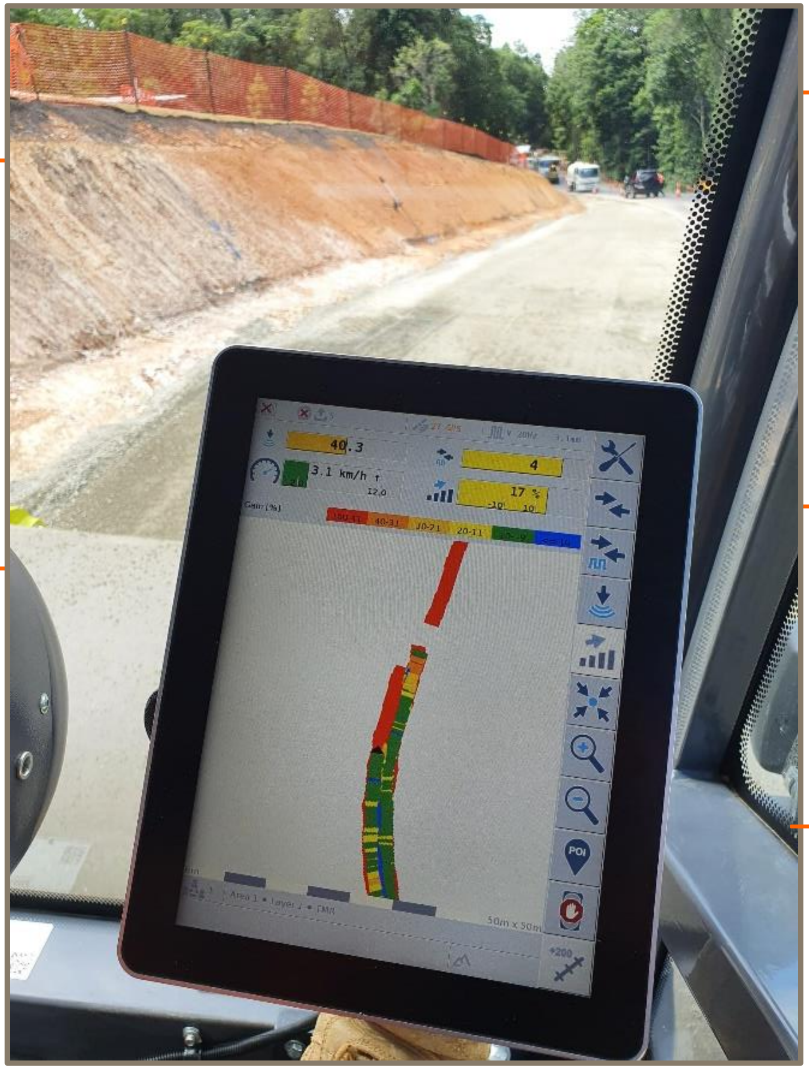
Operator Perspective – Better Visibility

Improved Context

Chainage / DXF linework adds more context for operator

Synchronisation

Always be aware of total pass count across the roller fleet everywhere on site



Connectivity

A new operator can see what has already been done

Data isn't lost on shift handover

Real Time

Data recorded and transmitted wirelessly to the office for improved QA

Safety

With the roller operator being guided by their screen, they are free to focus on their broader context

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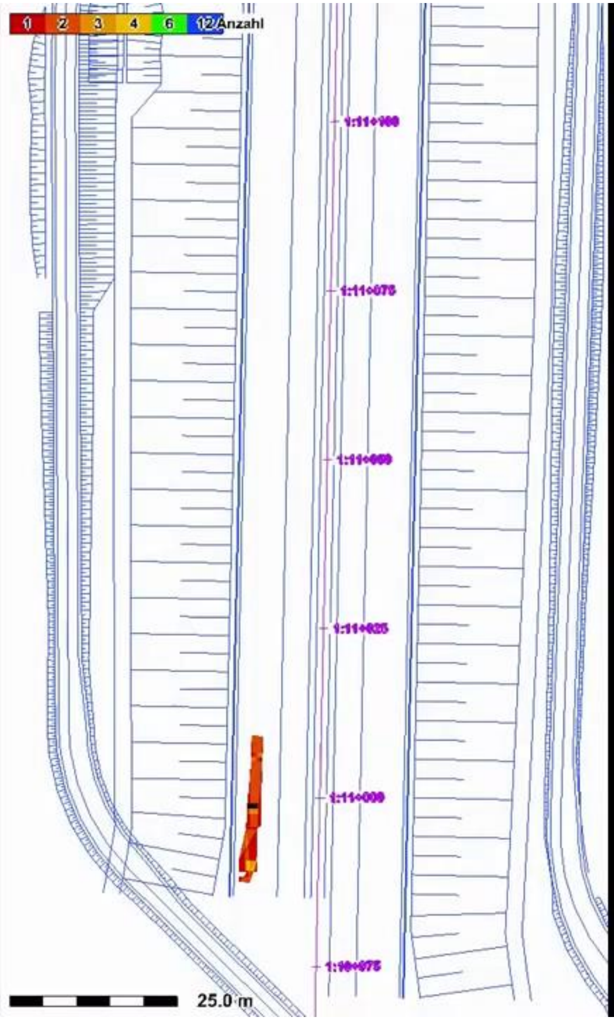
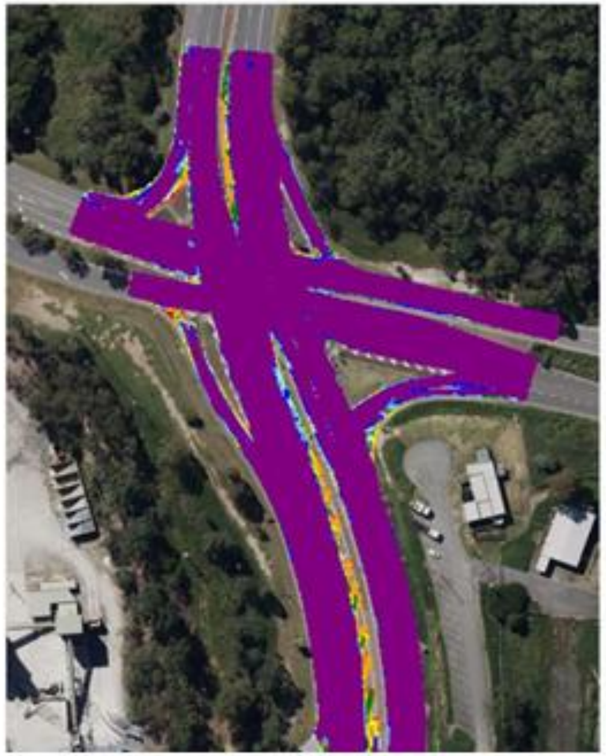
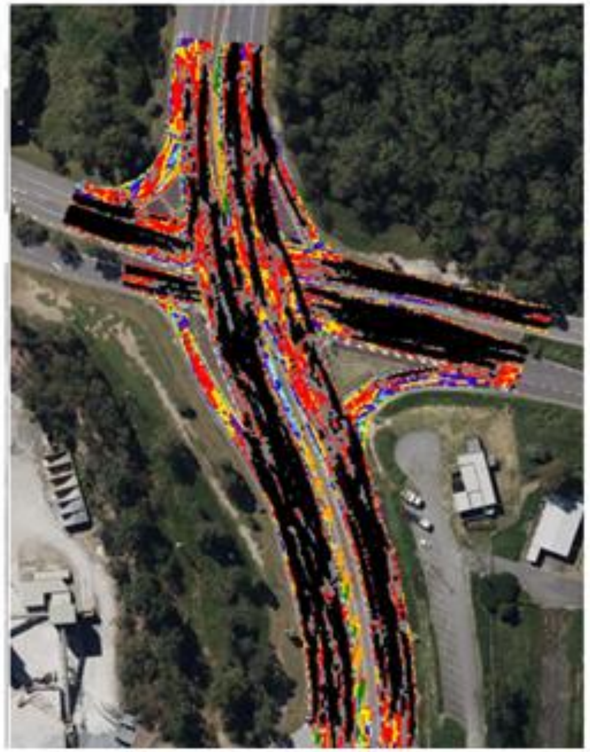
Operator Perspective – Office Validation & Reporting



Preventing Excessive Work and Over Compaction – Example



# of Passes	% Covered	
	Setting 1	Setting 2
No pass	4.4	4.4
1 Pass	0.7	0.7
2 Passes	2.2	2.2
3 Passes	1.3	1.3
4 Passes	2.1	2.1
5 Passes	2.4	2.4
6 Passes	3.2	3.2
7 Passes	3.7	3.7
8 Passes		4.5
9 Passes		5.0
10 Passes		5.6
11 Passes		5.6
12 Passes		6.0
13 Passes		6.1
14 Passes	80.1	6.0
15 Passes		5.9
16 Passes		5.8
17 Passes		5.4
18 Passes		4.9
19 Passes		4.1
20+ Passes		15.2



AfPA 19th AfPA International Flexible Pavements Conference
Safely Paving the way to Carbon Zero
30th Oct - 31 Oct -1st Nov 2023 | BCEC Brisbane QLD

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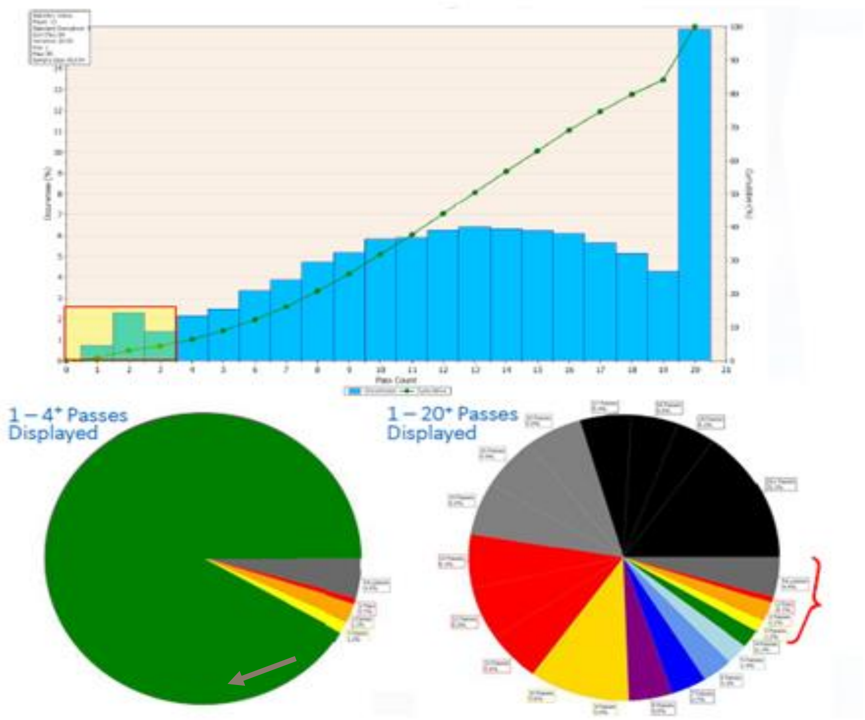
Preventing Excessive Work and Over Compaction – Example 2

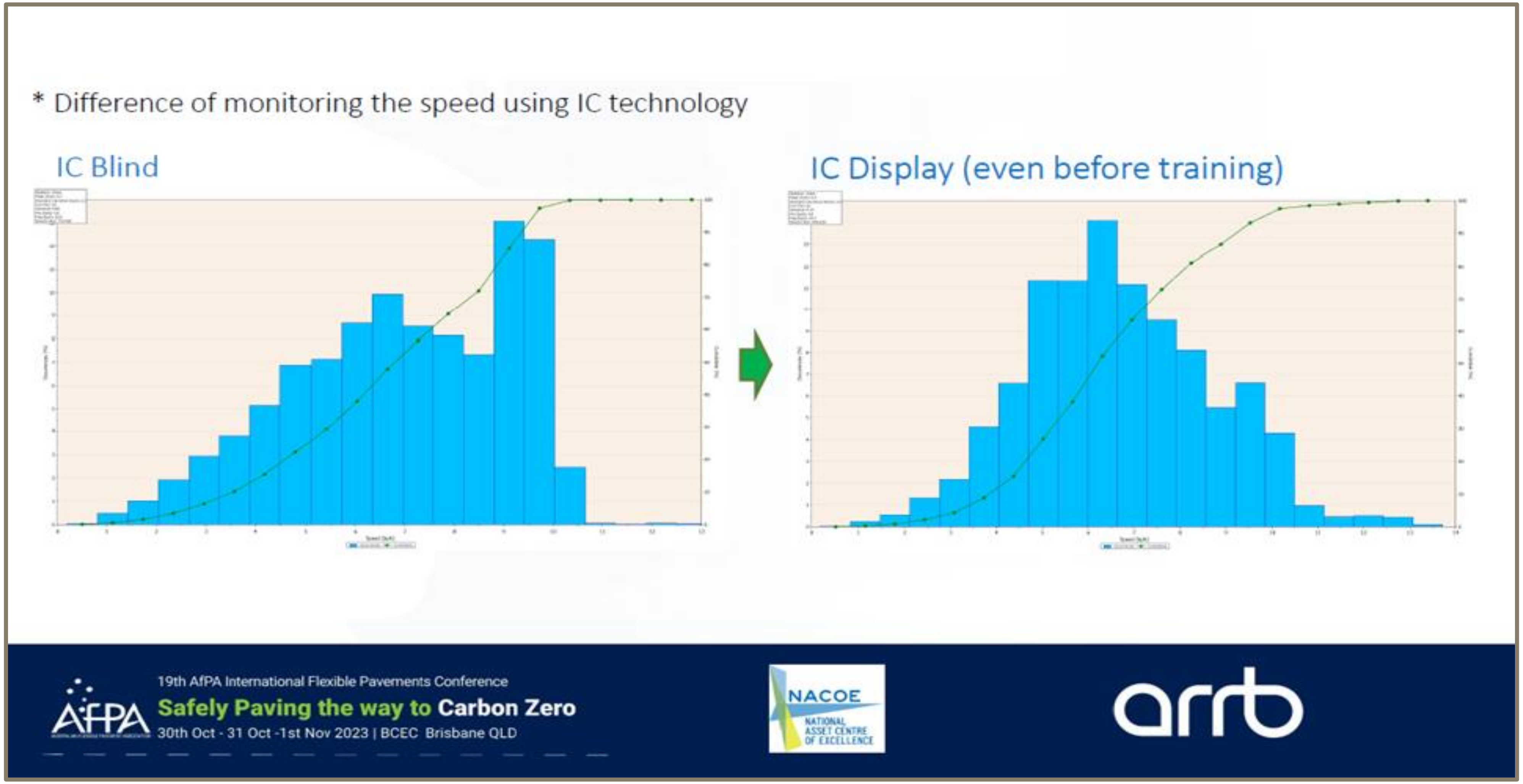


Considering the required # of passes (i.e. 4 passes), the area, and the practicality of the rolling process (and accommodate the overlaps).

153% Extra work (i.e. pass *m2)

Whilst 4.4% of the area was totally missed, & 8.6% of the area did not get the required # of passes.

Monitoring Rollering Speed



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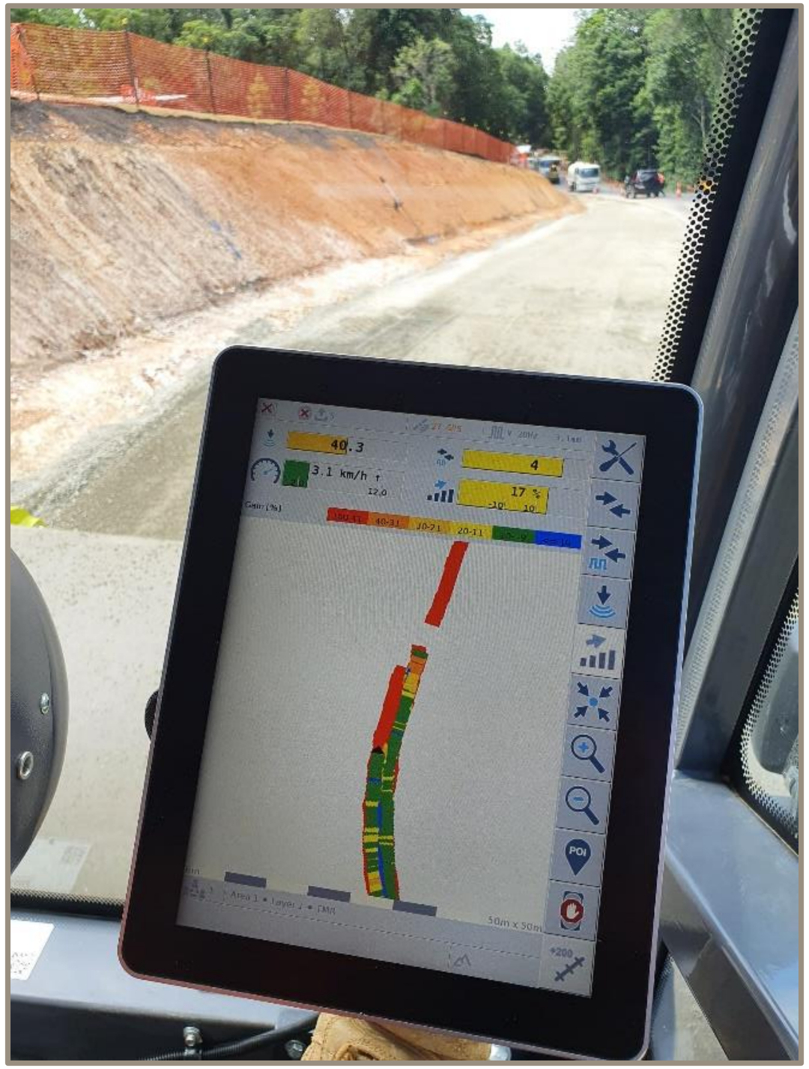
Pavement Response Stiffness Indication

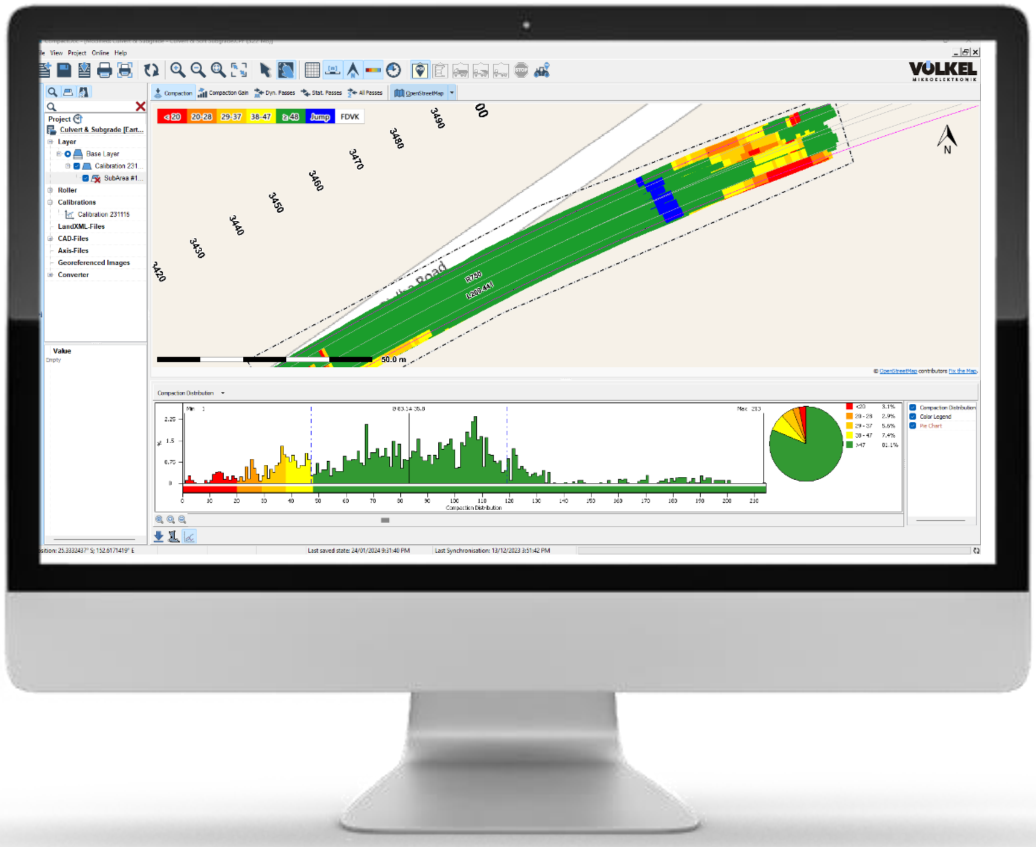
- Detect Soft Spots and Anomalies
- Provide 100% coverage - overcoming the issues with a limited number of spot tests for Quality Assurance purposes
- Enabling continuous placement of material with confidence (without waiting for traditional test results)
- Using Völkel Navigator IC system in combination with PANDA Variable Energy DCP and Light Weight Deflectometer, potential to increase placed loose layer lift thicknesses

Pavement Response Accelerometer

- Pavement response
    - Smart proof rolling
    - Stiffness indication
    - Stiffness Gain
- Vibration (amplitude & frequency and on / off)
- Oscillation (frequency and on / off)
- Unitless ICMV or MN/m2



Measure & Display Soil Stiffness



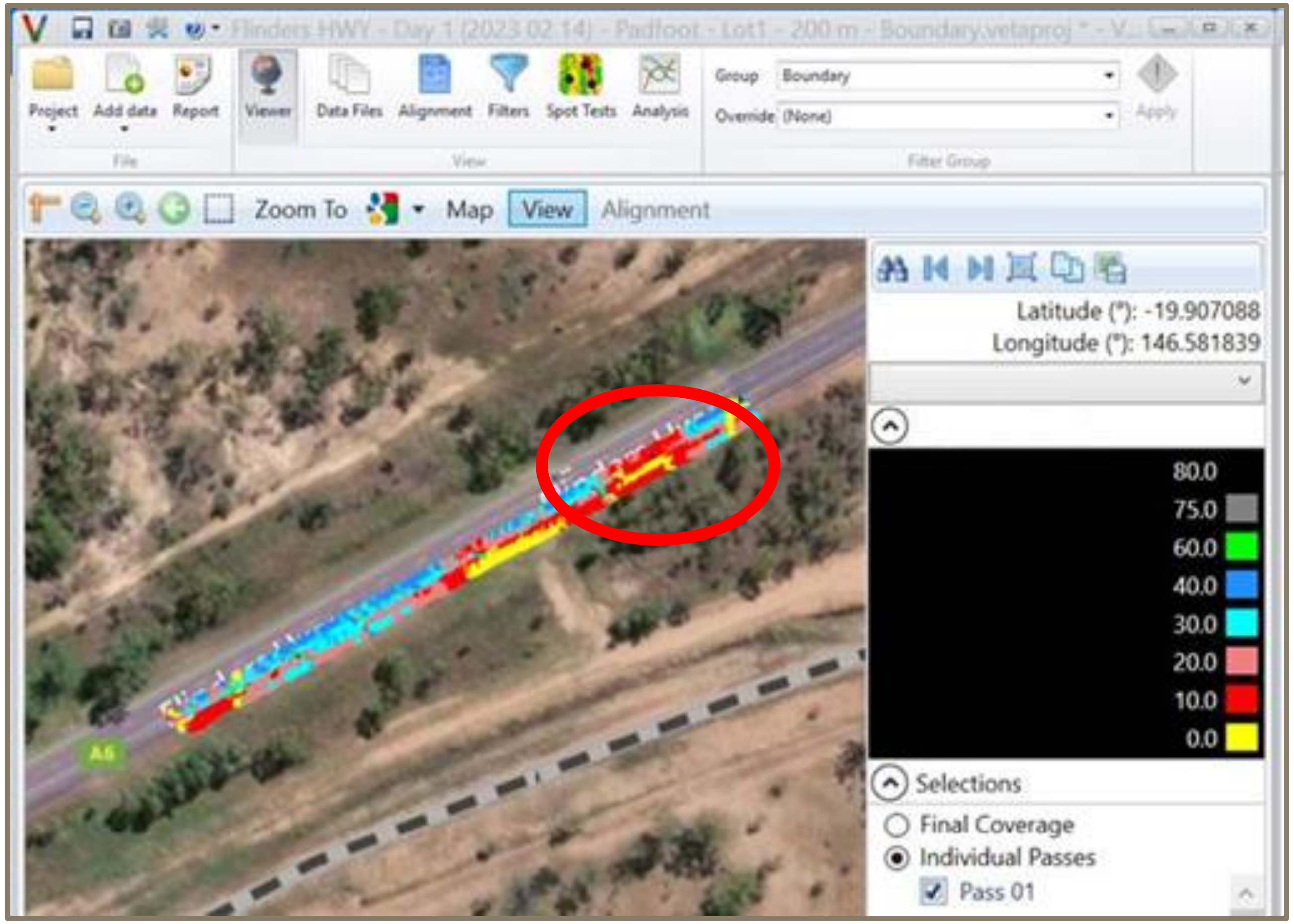
Uniform Compaction

Simple operator display clearly shows material stiffness vs target (dynamic) ensuring compliance to rolling patterns day or night

Identify Outliers

Measures everywhere you roll highlighting soft spots for more informed decision making by the geotechnical team

Detecting Soft Spots



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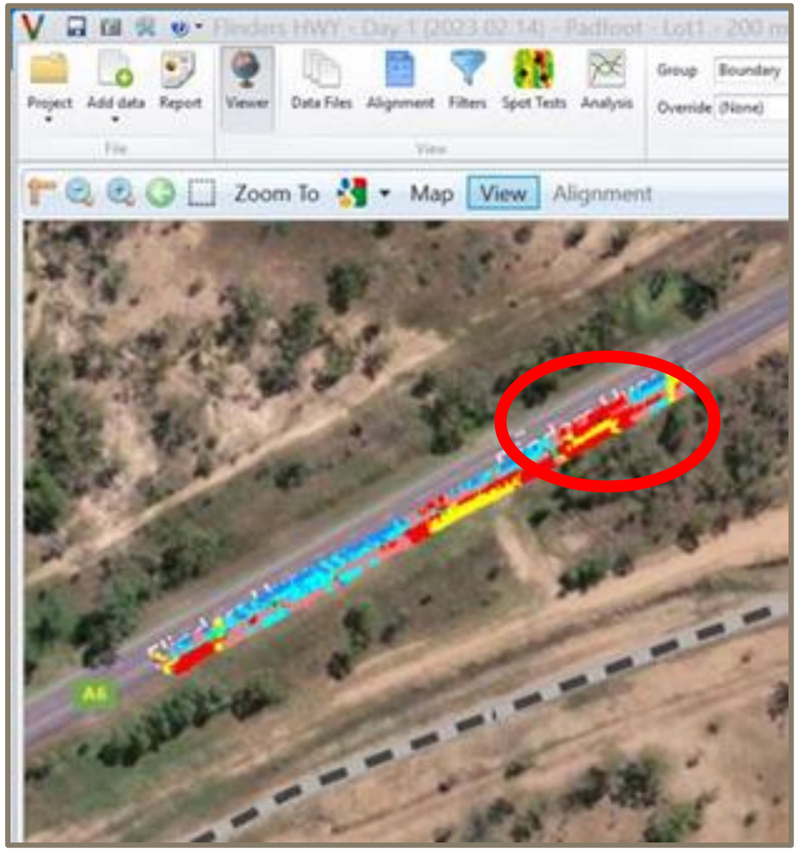
Detecting Soft Spots



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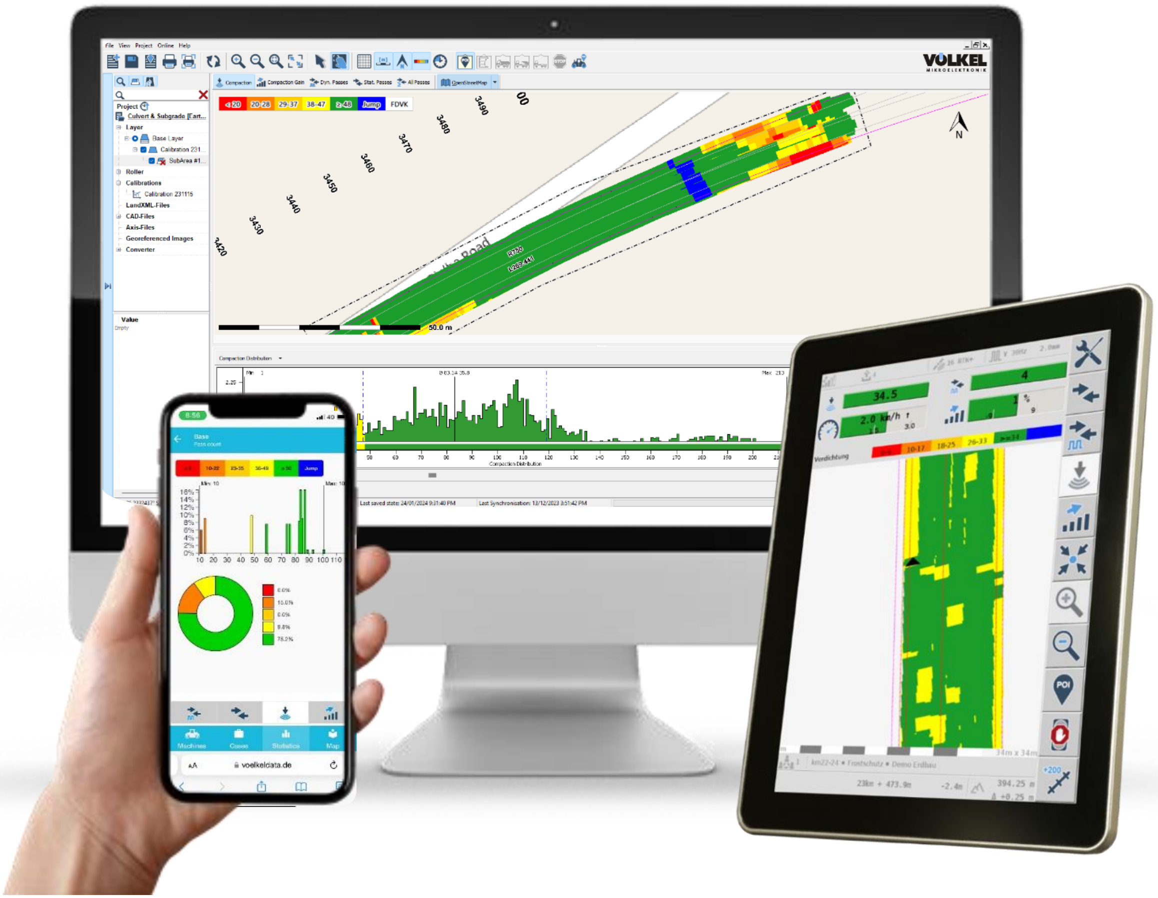
Measure & Display Soil Stiffness Indication



Continued monitoring

Always be aware of material stiffness pass by pass, layer by layer, everywhere on site

Access Soil Stiffness

Accelerometer mounted on drum measures stiffness confirming material compaction

Measure Stiffness Gain

Pass to pass change or Gain is recorded showing a gradual plateau of stiffness

How to DOUBLE the Placed Loose Lift Thickness

(and halve the number of lifts) without compromising quality

Australian Case Study

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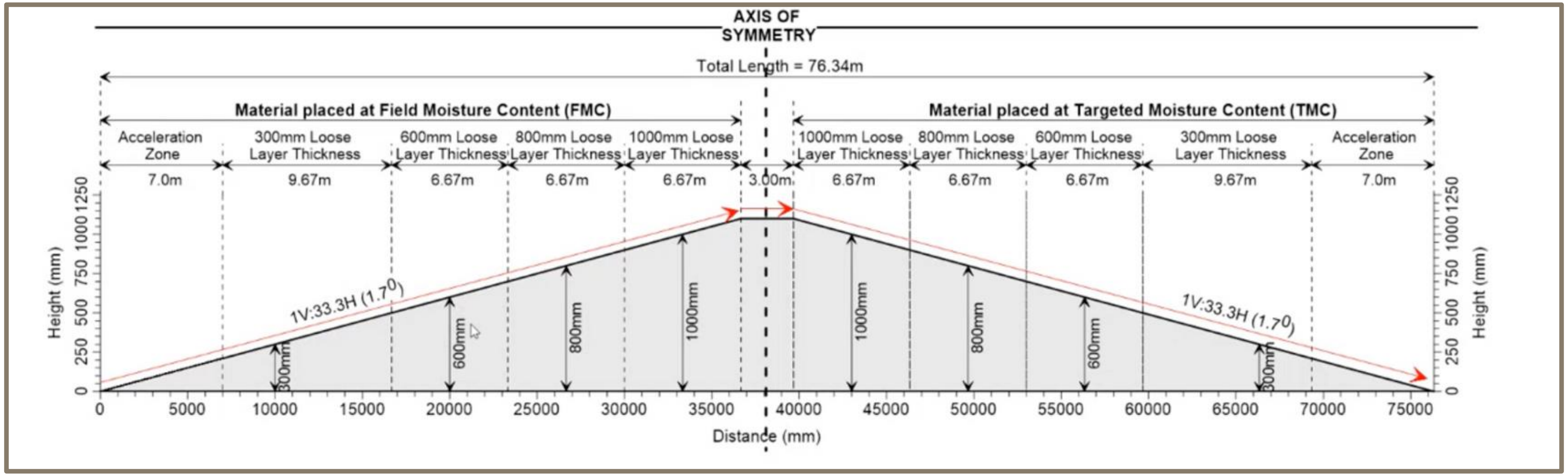
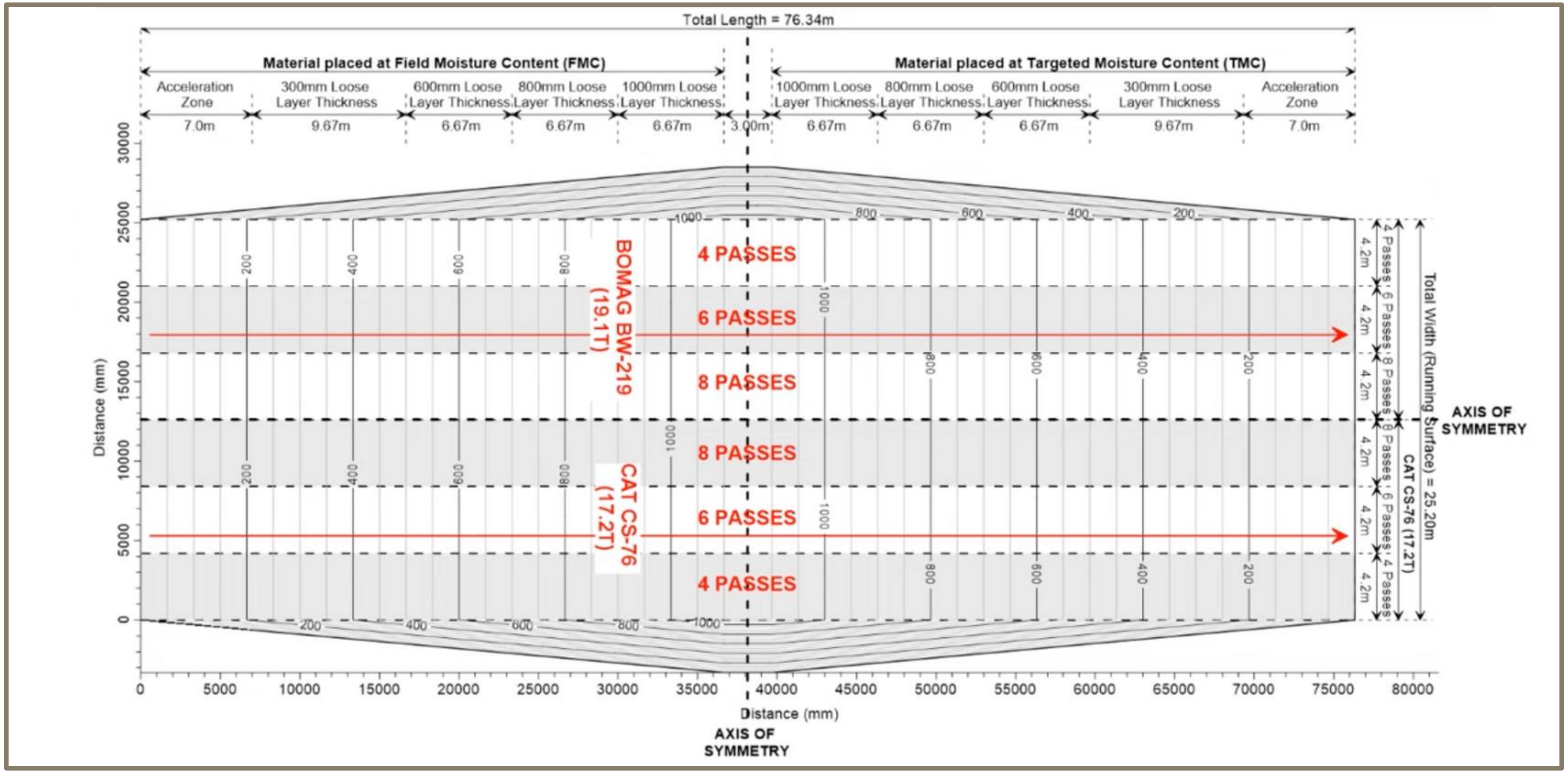
Full Scale Trial Embankments



- Approx. 75m Length x 25m Wide Trial Embankments
  - 3 Embankments
  - 3 Material Types being evaluated
- 4 Fill Thickness evaluated (all installed as loose layer thickness)
- 2 Moisture Contents considered - Field moisture Content and Moisture Conditioned

Full Scale Trial Embankments



- 2 Roller Models and Types - Padfoot and Smooth Drum
- 3 Frequencies of Roller Passes (4 Passes, 6 Passes, 8 Passes)

Deep Lift Specification

- Approved use of 600mm loose layer thickness (100% improvement on current earthworks specification)
  - Limit adopted as this was minimum uniform improvement observed. Specific configurations (material, roller, moisture condition) demonstrated even higher acceptable loose layer thickness
- Specification included a method specification - stated minimum roller type and compaction methodology (no. of passes)
- Key part of QA Regime included an Equivalence Table - Each alternative test method had a minimum threshold to be achieved for acceptance (and details of key test arrangements)

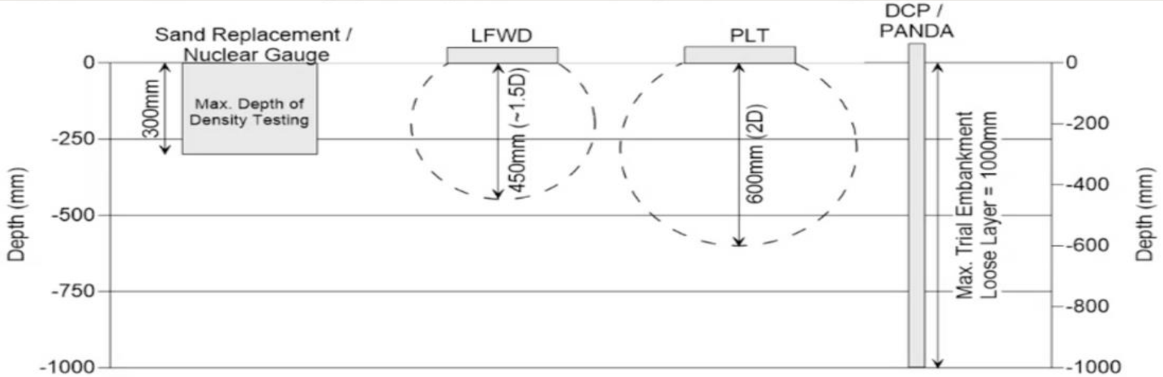
Table 14 Alternative field testing and equivalent results that correlate with 95% Compaction threshold

Test Name	Test Result equivalent to Sand Replacement determined Dry Density Ratio of 95%	Test Depth / Zone of Influence	Notes / Comments
Nuclear Density Gauge	Dry Density Ratio = 95%	250mm	Correlation needs to be confirmed for surface based Nuclear Density Gauge and Sand Replacement Tests
PANDA Probe	q_d = 10.0 MPa	Depth of Penetration	q_d = Cone Tip Resistance (suitably filtered to remove effect that presence of oversize may have on q_d parameter) Cone Tip Area = 2 cm²
Static Plate Load Test (PLT) or Equivalent (e.g. Falling weight Deflectometer)	E_{v2} = 60 MPa	~ 600mm	*Ev2* is determined by second loading cycle (i.e. 1st reloading cycle) All PLT testing to be completed using 300mm diameter plate
Light Falling Weight Deflectometer (LFWD)	$E_{LFWD-100kPa}$ = 45 MPa	~450mm	$E_{LFWD-100kPa}$ = insitu modulus determined under 100kPa applied test stress All LFWD testing to be completed using 300mm diameter plate Prima 100 model LFWD shall be utilised for LFWD tests

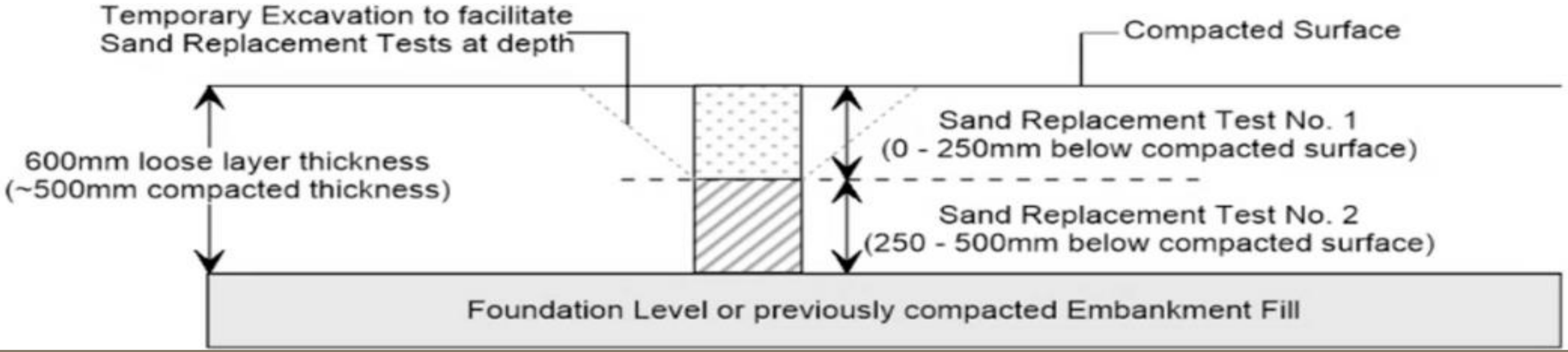
Material Specific

Deep Lift Specification

- Stakeholders was very keen to be able to prove full depth compaction had been achieved, as that was key part (limitation) of the existing QA



- Specification also included a provision for compliance with density QA regime, especially in first stages of specification in production



Key Findings Deep Lift - Compaction & Testing

- Early collaboration between designers, contractor and client and their technical advisers really important
    - Utilise early contractor involvement
- Don’t just put into the tender / specification documentation or worse, introduce part way through the project when participants have won the work based on a different compaction and testing regime
- Importance of using consultants with a track record implementing this approach builds confidence

THANK YOU!

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