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Use of the Light Falling Weight Deflectometer (LFWD) as a site investigation tool for residual soils and weak rock

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ABSTRACT: The Light Falling Weight Deflectometer (LFWD) is a surface based, dynamic plate load test that provides quick and direct measurement of the *insitu* modulus parameter of the near-surface. The LFWD's direct measurement of modulus negates the need to indirectly estimate the parameter via penetration or density testing, both of which have significant transformation errors associated with them. To demonstrate the potential use of the LFWD as an effective site investigation tool, two brands of LFWD were employed to assess the *insitu* modulus of a residual soil and weak sedimentary rock profile present along a significant infrastructure project in Queensland, Australia. The performance of both LFWDs was assessed and compared to other 'traditional' site characterisation techniques, including DCP profiling and laboratory (soaked) CBR testing. Characteristic *insitu* modulus parameters are presented, and variation thereof, for the range of material units that exist across the traditionally difficult to characterise residual soil to weak rock transition zone.

1 INTRODUCTION

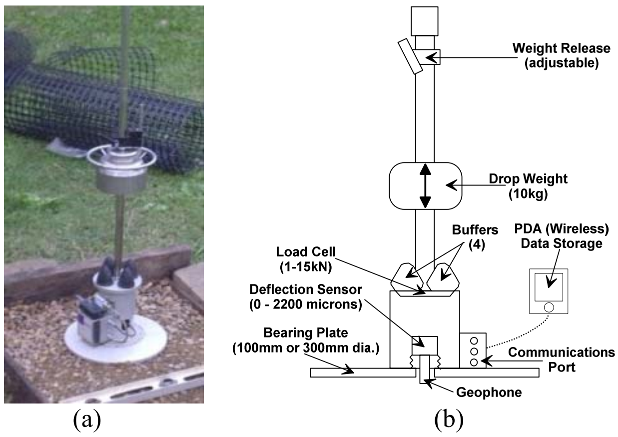
The Light Falling Weight Deflectometer (LFWD) is a surface based, dynamic plate load test that provides quick and direct measurement of a near-surface, composite *insitu* modulus parameter. The direct measurement of modulus by the LFWD negates the need to indirectly estimate the parameter – which is currently frequently achieved by using the results of penetration (e.g. Dynamic Cone Penetrometers, DCPs) or density test techniques. Such methods may have significant transformation errors associated with them, especially if "universal" correlations are blindly applied to field test results.

Previous focus on the LFWD development has primarily related to its use as a Quality Assurance (QA) tool; for example, the verification that design parameters are met for base, sub-base and pavement layers (e.g. Vennapusa and White, 2009; Nazzal et. al., 2007; Fleming et. al, 2000). In this paper, the use of the LFWD as an effective site investigation tool for subgrade assessment is demonstrated.

Unlike processed pavement materials, which usually exhibit uniform or controlled Particle Size Distributions (PSDs), the materials that typically exist *insitu* across the residual soil to weak rock transition zone are non-homogenous. Often a gradational increase in the gravel (or larger) sized component of rock fragment / parent rock material also occurs across the weathering profile. Such properties may cause many site investigation techniques to become ineffective within such material profiles.

2 LIGHT FALLING WEIGHT DEFLECTOMETERS (LFWDs)

Insitu testing to determine the Young's Modulus of the composite material can be achieved by the use of LFWDs. Such instruments, as shown in Figure 1, are quasi-static plate load tests (PLTs), in which a sliding 10kg weight is manually raised along a vertical guide rod and dropped onto a rigid base plate. The load pulse – generated when the weight is dropped upon the rubber dampers – passes through the rigid plate and into the ground as a uniform stress. Depending on the LFWD manufacturer (refer Table 1), the imparted load can either be measured with a load cell or simply assumed to be a standard magnitude. An accelerometer or geophone measures the resulting deflection of the ground below the plate centre.



(a) (b)

Figure 1. Prima 100 LFWD (a) during fieldwork and (b) in cross-section in cross-section (after Fleming et. al., 2007)

Table 1. Comparative manufacturer details of LFWDs studied

Aspect of Equipment	ZFG 2000	Prima 100
Manufacturer	Zorn	Sweco (formerly Grontmij A/S)
Test Stress	All test loads assumed fixed at 7.07kN = 100kPa	Independently measured for each weight drop via loadcell
Plate Diameter	300mm	100mm, 300mm
Plate Material	Steel	Aluminum
Plate Thickness / Weight	20mm / 13.9kg	15 - 20mm / 5.9kg
Deflection Measure	Accelerometer mounted on plate	Geophone in contact with ground
Poisson's Ratio (ν) and Stress Reduction Factor (S)	(S, ν) fixed such that $S(1 - \nu^2) = 1.5$	Fully editable by user based on tested material

As both force and deflection values are measured over the duration of the load pulse, the composite Young's Modulus (E_{LFWD}) over the zone of test influence can thus be derived by the classic static elastic theory (Boussinesq elastic half-space) equation, as shown in Equation 1. Previously identified limitations relating to the application of static elastic theory for interpretation of LFWD results are detailed in Fleming et. al. (2007), and include a phase lag between the timing of the observed peak force and maximum deflection values.

$$E_{LFWD} = [A \text{ x } P \text{ x } R \text{ x } (1 - \nu^2)] / d_0 \qquad (1)$$

Where: A = Plate rigidity factor (π/2 for rigid plate); P = Maximum Contact Pressure; R = Radius of plate ν = Poisson's Ratio; d_0 = Peak deflection

Lacey et. al. (2012, 2013) have previously compared the LFWD measured modulus parameter with the results of PLT and DCP tests, for fieldwork completed upon both processed and natural materials. Lacey (2016) also demonstrated that the E_{LFWD} parameter required standardisation to a 'reference' stress state. As the modulus parameter is stress-dependent, it is thus affected by the weight of hammer, drop height and plate diameter utilised. A value of 100kPa was used as the 'reference' stress to compare results for this study ($E_{LFWD-100kPa}$).

For this study, two (2) types of LFWD were used for the side-by-side testing completed in order to assess the differences in the reported E_{LFWD} parameter. The LFWDs utilised for this study were (a) the Prima 100 (built to ASTM E2835-07) and (b) the Zorn ZFG-2000 (built to ASTM E2583-11). Table 1 details the key variations between these two (2) types of LFWD.

3 FIELD AND LABORATORY TESTING PROGRAM

The completed *insitu* testing program formed a subset of a larger site investigation undertaken for a major highway project in South East Queensland, Australia. A number of *insitu* testing techniques were completed at side-by-side locations within 14 individual test pits at near surface depths of up to 1.2m. The field tests techniques employed included LFWD (2 types), density (sand replacement and nuclear gauge) and DCP profiling. At all locations a residual soil to weak rock profile was encountered (i.e. no alluvial material units). Laboratory testing of representative samples was also completed, allowing classification of the studied materials to Australian Standards (AS1726) and in terms of soaked CBR.

Typical material unit compositions are shown in Table 2. Although no PSD testing was completed on Extremely Weathered (XW) rock materials, a general trend of fines content reduction / gravel content increase of the materials was observed over the full 'Residual Soil' to Highly Weathered (HW) rock weathering interval. A similar trend for the Weighted Plasticity Index (WPI) was also observed, with all values suggesting that the studied materials had 'very low' potential for volume change. These

Table 2. Summary of laboratory determined classification tests, categorised by material unit

Material Unit	Moisture Content (%)	Atterberg Limits (%)				Particle Size Distribution (%)			Weighted Plasticity Index (WPI)
		Liquid Limit	Plastic Limit	Plasticity Index	Linear Shrink.	Gravel / Cobbles	Sand	Fines	
Residual – Granular	10.0 (7 – 13)	16.8	15.8	1.0	0.6	40	48	12	43
Residual – Cohesive	19.1 (14 – 25)	44.5 (39 – 51)	23.4 (19 – 27)	21.0 (18 – 27)	10 (8 – 11)	24	11	65	1232
XW Rock	11.3 (5 – 18)	50.8 (50 – 51)	23.6 (21 – 26)	27.2 (25 – 29)	12.8 (11 – 14)	–	–	–	–
XW / HW Rock	16.5 (13 – 20)	39.5 (34 – 45)	23.9 (21 – 27)	15.6 (13 – 18)	6.4	54.5 (49 – 60)	12.5 (11 – 14)	33 (26 – 40)	612 (442 – 783)
HW Rock	9.0 (3 – 14)	30.6 (23 – 36)	20.2 (19 – 23)	10.5 (4 – 16)	5.4 (3 – 8)	64.3 (61 – 70)	20.3 (15 – 25)	15.5 (12 – 22)	195 (116 – 312)

Table 3. Summary of *insitu* modulus values determined by LFWD testing, categorised by material unit

Material Unit	$E_{LFWD-100kPa}$ (MPa) – ZFG 2000 LFWD				$E_{LFWD-100kPa}$ (MPa) – Prima 100 LFWD			
	Interquartile Range	Mean	Median	CoV (%)	Interquartile Range	Mean	Median	CoV (%)
Fill	10.7 – 13.7	11.9	13.2	27%	16.6 – 22.1	20.0	17.3	30%
Residual Soil - Granular	23.9 – 24.0	24.0	24.0	1%	31.7 – 50.8	41.2	41.2	66%
Residual Soil - Cohesive	13.6 – 20.4	16.6	14.5	35%	19.2 – 50.0	37.2	34.5	64%
XW Rock	23.2 – 37.7	31.1	28.5	47%	64.6 – 76.2	69.8	72.0	17%
XW / HW Rock	28.6 – 41.7	35.0	35.6	37%	70.9 – 96.7	85.1	79.8	31%
HW Rock	38.7 – 46.5	40.9	44.4	29%	119 – 152	134	139	25%

trends were considered typical of the gradational transition between residual soil and weak rock materials commonly encountered within QLD, Australia (Lacey, 2016).

4 INSITU MODULUS INCREASE ACROSS SOIL – WEAK ROCK TRANSITION

The *insitu* modulus (E_{LFWD}) parameter determined from each of the two (2) LFWD equipment types utilised in this study are summarised in Table 3. All results were standardised to the E_{LFWD} parameter observed under the application of a 100kPa test stress. A total of 23 side-by-side tests – using both ZFG-2000 and Prima 100 – were completed, with both LFWDs utilising 300mm diameter plates. After data processing via previously published standard methodologies (Lacey, 2016), three (3) datapoints were excluded, resulting in a dataset of 20 E_{LFWD} pairs (n = 20) being used to investigate the correlation between the two (2) LFWD instruments. Table 3 summarises the variation in the E_{LFWD} parameter categorised by both material unit and LFWD equipment.

It is clear that an increase in *insitu* modulus (i.e. decrease in measured LFWD plate deflection) can be strongly associated with the logged decrease of weathering effects within the rockmass. As shown in Figure 2 (for the Prima 100 LFWD results), when 'characteristic' E_{LFWD} values are calculated for each of the weathering classes tested, a near linear relationship is produced across the full 'residual soil' to 'HW rock' weathering interval. This general trend of E_{LFWD} parameter increase was observed regardless of the LFWD equipment utilised, although the magnitude of the reported modulus parameter differed significantly. Over the range of tested materials, the measured E_{LFWD} parameter increased by between 225% (Zorn LFWD) to 350% (Prima LFWD). The magnitude of this modulus increase is approximately the same as the increase observed within typical Shear Wave Velocities of SEQ materials over the same weathering profile interval, whereby an equivalent increase of between 270% and 320% has been observed (e.g. Lacey, 2016).

The surface based LFWD test was successfully applied across the full spectrum of tested 'residual soil' to 'soft rock' material. This finding demonstrates the suitability of the LFWD as a test technique that can be used to investigate the variation in material parameters across the full soil to rock transition. By contrast, the increase in the gravel and the large particle content across the transition between 'residual soil' and significantly weathered, 'soft' rock (refer Table 2) limits the applicability of many traditional site investigation test techniques. As identified by Lacey (2016) CPT tests have been found to typically refuse within residual soil materials within South East Queensland, whilst hammer driven penetration tests (i.e. DCP and SPT) can be expected to refuse within, or provide erroneous results for, XW-HW (or better) rock materials. For competent rock materials (i.e less weathered than Highly Weathered (HW) materials), it would be expected that rock coring site investigation techniques and rock strength testing would become suitable to characterise material parameters.

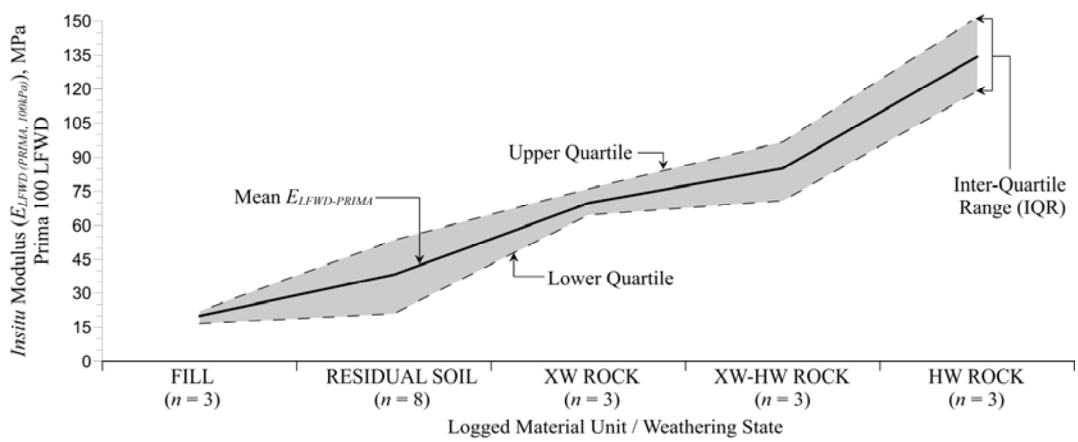
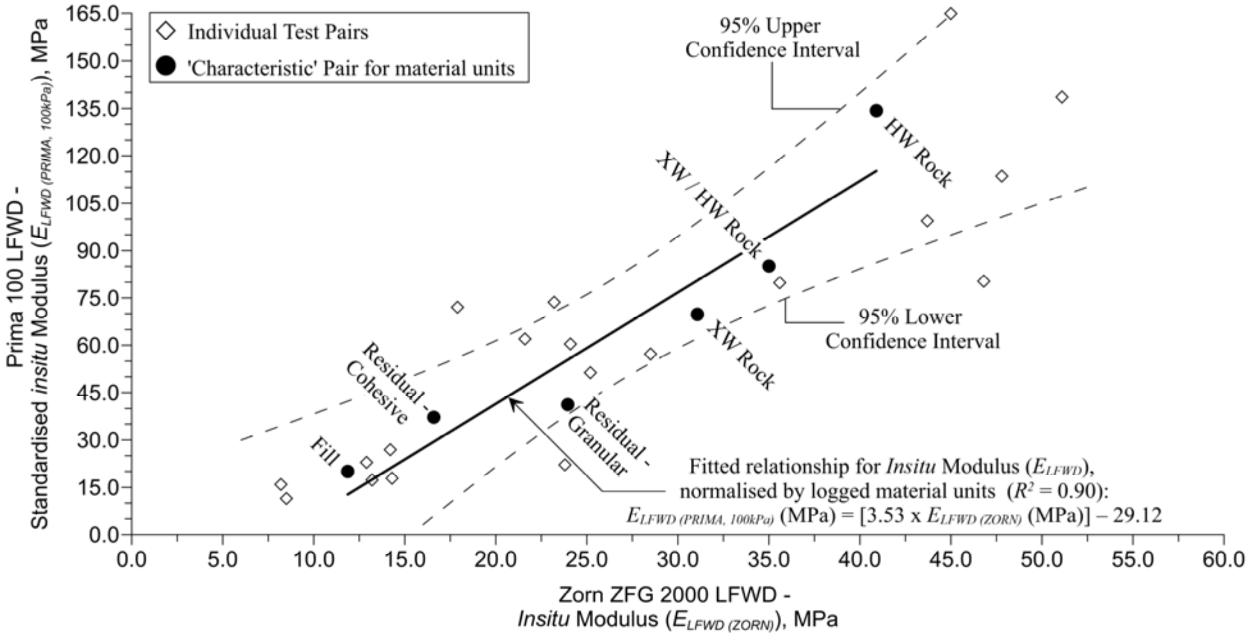


Figure 2. *Insitu* modulus measured by Prima 100 at 100kPa test stress ($E_{LFWD-PRIMA}$) categorised by weathering state of material

Figure 3. Comparison of *insitu* modulus parameter (E_{LFWD}) measured by Prima 100 and ZFG-2000 LFWD



5 COMPARISON OF RESULTS OBTAINED BY LFWD EQUIPMENT VARIATIONS

Having identified that the LFWD test equipment was suitable for use to assess the comparative stiffness of material units across the weathering profile between ‘residual soil’ and ‘HW rock’, the difference in the Young’s Modulus (E) between the two (2) variants of LFWD equipment used for the site testing was also assessed.

A regression analysis was completed for both the individual LFWD test pair data and using the characteristic E_{LFWD} values determined for each material unit. In both cases, a strong, positive linear relationship between the Zorn and Prima 100 *insitu* modulus values (E_{LFWD}) was demonstrated ($R^2 > 0.75$). Equation 2 and Figure 3 present the relationship between the characteristic E_{LFWD} values determined for each material unit.

$$E_{LFWD\ (PRIMA\ 100)} = [3.53 \text{ x } E_{LFWD\ (ZFG\text{-}2000)}] - 29.12 \quad (R^2 = 0.90, p < .05) \qquad (2)$$

Where all E_{LFWD} values are in MPa.

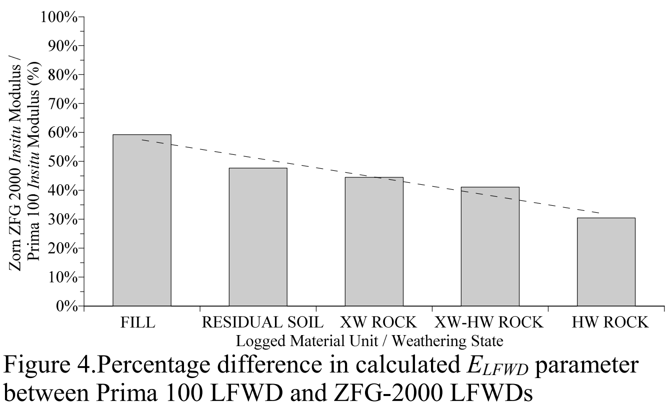


Figure 4.Percentage difference in calculated E_{LFWD} parameter between Prima 100 LFWD and ZFG-2000 LFWDs

By comparison of the average E_{LFWD} values determined by each LFWD instrument and for each of the weathering classes tested, the varying relationship between the two (2) E_{LFWD} values was again demonstrated. As presented in Figure 4, the difference between the comparable E_{LFWD} values linearly decreases as the stiffness of the tested material increases. The E_{LFWD} value determined by the ZFG-2000 equipment decreases from 48% to 30% of the Prima 100 value over the ‘Residual Soil’ to ‘HW Rock’ weathering interval.

The range of deflections produced by the Prima 100 LFWD at a 100kPa test stress ($\bar{x} = 0.6$mm, $\sigma = 0.4$mm) were lower than comparative values observed with the ZFG-2000 LFWD ($\bar{x} = 1.2$mm, $\sigma = 0.6$mm). As the calculated ‘*insitu* modulus’ is a deflection dependent parameter (refer Equation 1), then the higher deflections recorded by the ZFG-2000 instrument resulted in consistently lower ‘*insitu* modulus’ (E_{FLWD}) values being determined (for all other variables being standardised).

Previous studies (e.g. Lacey et. al., 2012; Nazzal et. al., 2007) have identified that the E_{LFWD} values produced using the Prima 100 LFWD equipment equate approximately to modulus values produced by traditional test methods, such as full scale Falling Weight Deflectometers (FWDs) and static Plate Load Tests (PLTs). Accordingly, it is recommended that the E_{LFWD} parameter produced by the ZFG-2000 instrument are not directly adopted as ‘subgrade modulus’ values or use in applications as a direct replacement for parameters determined by ‘traditional’ *insitu* modulus measurement techniques. As shown by the results of the current study and Figure 4, the additional factor that is required to be applied to the ZFG-2000 results varies based on the stiffness of the material.

Table 4. Typical DCP and *insitu* modulus material properties for range of material units investigated

Dynamic Cone Penetrometer (DCP)		*Insitu* Modulus, $E_{LFWD-100kPa}$ (MPa)		
Blows / 100mm rod penetration (no.)	Rod penetration / Hammer Blow (mm)	Prima 100 LFWD[1]	ZFG-2000 LFWD[2]	Material Unit / Weathering State
3	33	16	8	SOIL (Fill / Residual Soil)
4	25	20	10	
5	20	24	12	
10	10	43	21	Residual Soil to XW/HW Rock
20	5	76	36	XW / HW Rock
25	4	92	42	
33	3	116	53	HW Rock

[1] Modulus calculated assuming a total value of 1.5 for the Stress Reduction Factor and Poisson's Ratio pair (S, v)
[2] Additional conversion required to produce a design 'subgrade modulus' value from ZFG-2000 results

6 SUMMARY OF INSITU PARAMETERS FOR RESIDUAL SOILS AND WEAK ROCK

Of the 23 sites where comparative LFWD testing was completed, a Dynamic Cone Penetrometer (DCP) test profile extended to a depth below the level of LFWD testing for 22 sites. A correlation that related the penetration rate (PR) of the DCP test and the E_{LFWD} relationship was determined for the range of materials tested. This relationship builds on previously published DCP:E_{LFWD} correlations (e.g. Lacey, 2016; Nazzal 2007) and extends such relationships to the stiffer materials (i.e. lower PR values) investigated by this study.

Table 4 summarises the relationship between the typical DCP penetration rates and comparative *insitu* modulus (E_{LFWD}) values that were determined based on the data collected by this study. These results are anticipated to be generally applicable to residual soil and soft rock profiles found throughout SEQ, and general material and weathering state descriptors expected to be associated with each result are also provided in Table 4.

7 SOAKED vs. INSITU CBR VALUES

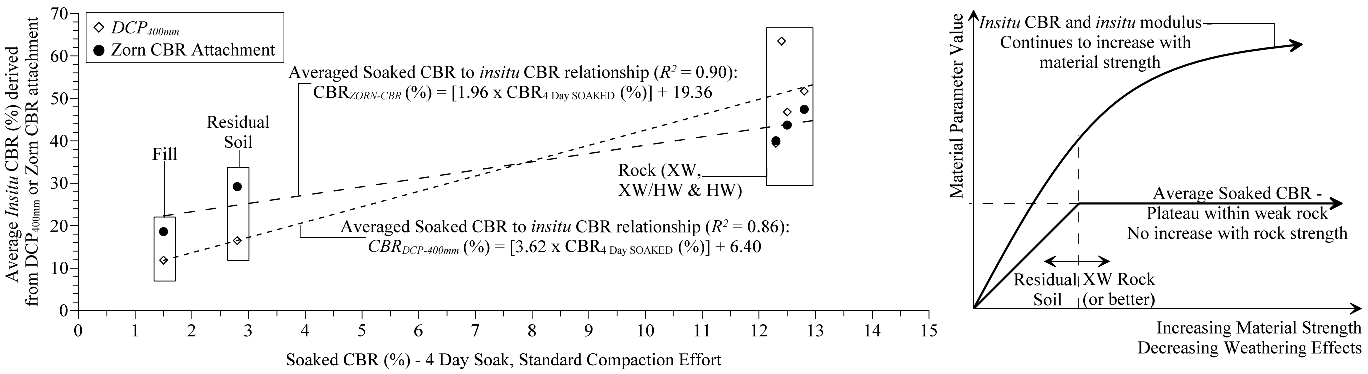
California Bearing Ratio (CBR) values are traditionally used to estimate the design modulus for embankment and pavement projects. Examples of this include CBR:*E* relationships included in standard design guidelines such as NAASRA (1987) or ASSHTO (2002).

In the study undertaken, both *insitu* and laboratory CBR values were determined. *Insitu* CBR values were determined via (a) direct measurement using a specialised CBR attachment for the ZFG-2000 LFWD equipment; (b) inferred from the results of DCP testing (adopting the NAASRA defined DCP_{PR}:CBR relationship). Laboratory determined CBR values were calculated as per AS1289.6.1.1; using samples soaked for four (4) days and prepared using standard compaction techniques.

For the dataset of soaked CBR values ($n = 14$), correlations were attempted to be made between the individual data pairs of *insitu* CBR values. Regardless of the method of *insitu* CBR calculation, no statistically significant relationships were found that related *insitu* to laboratory determined CBR values. This result (i.e. non-correlation between soaked CBR and *insitu* test pairs) was expected, as the soaked CBR test involves a fundamental change in both material state and composition – the removal of the oversize fraction of the sample and the subsequent compaction of material. The applied compactive effort would be expected to break inter-particle bonds present within the residual soil and weathered rock, and thus remove the structure that the relict rock structure provides to such materials.

When characteristic *insitu* and soaked CBR values were determined for each material unit, a strong, positive linear relationship could be demonstrated that related the results of the *insitu* and laboratory based tests ($R^2 > 0.85$). Figure 5a presents the relationship derived for the direct (ZFG-2000) and indirect (DCP via NAASRA relationship) estimation of *insitu* CBR respectively. However, due to the small dataset used ($n = 5$), the values produced via this relationship should be interpreted cautiously.

The laboratory determined, soaked CBR results displayed a plateauing across the XW to HW rock materials (12% < Soaked CBR < 13%) compared to the continually increasing CBR values produced by the results of *insitu* testing. As conceptually shown in Figure 5b, this observation has been interpreted to indicate the effect of the relict rock structure and oversize particles present within the weathered rockmasses. This finding also shows the highly conservative nature of adopting soaked CBR test results as representative of *insitu* conditions material properties associated with residual soils and weak rock materials. It should be noted that the CBR test is not applicable for samples with greater than 20% oversize materials (as per AS1289), yet continues to be used for such materials, due to the absence of a more reliable or convenient test.



(a) (b)

Figure 5. (a) Soaked CBR (%) compared to *insitu* measured CBR (%) values, categorised by weathering state of material (b) conceptual difference between *insitu* and soaked CBR values over residual soil / weak rock profile.

8 CONCLUSIONS

The methodology and analyses detailed within this study demonstrates the successful use of LFWD equipment to characterise the *insitu* modulus parameter (E_{LFWD}) across a wide range of comparatively incompressible materials; from stiff residual soils to highly weathered, low strength rock. The suitability of the LFWD to be used for subgrade assessment across the full residual soil / weak rock interface has been demonstrated.

Other conclusions that can be observed based on the side-by-side testing completed and correlation of test results include:

- Although strongly correlated, the Zorn ZFG 2000 LFWD instrument will routinely produce deflections of higher magnitude than the Prima 100 LFWD instrument, and that the relationship between the Zorn ZFG 2000 and Prima 100 determined E_{LFWD} values varies based on the stiffness of the material undergoing testing;
- The strongest relationship between LFWD and DCP test results occurred when the DCP profile over the 400mm depth interval below the LFWD test was considered (i.e. zone of influence of LFWD equates to 1.33 x Plate Diameter);
- Strong relationships between characteristic *insitu* modulus, *insitu* CBR and soaked CBR values were developed when the data was normalised for weathering state of the tested material. Significant variations in laboratory determined (soaked) CBR values – likely due to material grading and the varying proportion of oversize materials – prevented direct comparison of test results for individual samples; and
- *Insitu* CBR values reflect the field conditions at the time of testing, whilst soaked CBR values are based on remoulded samples and applying 'flood' conditions. For the site investigated, soaked CBR values appeared to plateau at 12 – 13% across the full rock profile assessed (regardless of weathering state), whilst the *insitu* CBR values continued to increase as per the weathering grade.

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