Direct Validation of Design Parameters of Near-Surface Materials during Construction Phase

Dr. D. Lacey[1], FIEAust, CPEng., Dr. B. Look[2], FIEAust, CPEng., and Dr. J. Lee[3], FIEAust, CPEng.

[1]Senior Geotechnical Engineer, FSG Geotechnics + Foundations, P.O. Box 1241, Spring Hill, Queensland, Australia, 4004; PH (07) 3831-4600; email: dlacey@fsg-geotechnics.com.au
[2]Principal Geotechnical Engineer, FSG Geotechnics + Foundations, P.O. Box 1241, Spring Hill, Queensland, Australia, 4004; PH (07) 3831-4600; email: blook@fsg-geotechnics.com.au
[3]Principal Professional, Future Transportation Infrastructure, Australian Road Research Board (ARRB), 21 McLachlan St, Fortitude Valley, Queensland, Australia, 4006; PH (+61) 410 110 050; email: jeffrey.lee@arrb.com.au

ABSTRACT

This overview paper discusses a number of innovative *insitu* test techniques that could potentially be incorporated into Quality Assurance / Quality Control (QA / QC) for the assessment of near-surface materials during the construction phase of earthworks projects. The limitations of traditional QA test regimes (density-based assessments) and other tests frequently adopted for field assessment during the construction phase of projects (CBR and DCP) are initially discussed, with a critique of the continued use of index tests for such material evaluations provided. A number of alternative test techniques that are capable of rapid, direct *insitu* measurement of stiffness and strength parameters is made, presenting the Light Falling Weight Deflectometer (LWD), Borehole Shear Test (BST) and Variable Energy Dynamic Cone Penetrometer (PANDA Probe) as viable alternative assessment methods. The *insitu* parameters provided by these alternative tests can be used to directly evaluate if design parameters are being met onsite and, based on the authors extensive experience using each tool within recent major Australian construction projects, the advantages of using such innovative tools and developing project-specific thresholds for adoption of these tools within a QA / QC test regime, are discussed. Current limitations preventing the widespread implementation of these alternative test techniques are also identified.

Keywords: Compaction, LWD, PANDA Probe, Borehole Shear Tester (BST), Quality Control (QC)

1 INTRODUCTION

The current state of *insitu* testing for Quality Assurance (QA) or design parameter verification of near-surface materials within infrastructure projects across Australia is largely a result of 1930's to 1970's technology. Assessment of the base of cuttings, subgrades and embankment fills are typically evaluated using test techniques that provide results that are at least one step-removed from the design parameter they are intended to appraise. This is a significant limitation to the effectiveness of *insitu* test program, due both to the need for incorporation of a generic correlation or, worse, an unverified assumption to interpret the test result. A review of the acceptable test methods for QA as per the current Earthworks Specifications published by many major road authorities verify this assertion (e.g. NSW's Roads and Maritime Services (RMS) – *R44 – Earthworks* (2014); QLD's Department of Main Roads and Transport (TMR) – *MRTS04 General Earthworks* (2018); or VIC's VicRoads – *Standard Section 204 Earthworks* (2015)); with a large portion of material evaluation procedures mandating assessments be completed utilising density testing (1930's technology for Proctor mould testing; 1970's technology for Nuclear Density Gauge Testing) or California Bearing Ratio (CBR) testing (1930's technology).

Whereas such testing may have been considered state-of-the-art when initially adopted, and indeed may have successfully delivered projects to the required quality, the applicability of such assessment methods has since been superseded. Recent technological advances – over the last 20 years – have delivered to the earthworks construction industry a range of tools that facilitate direct and rapid, *insitu* assessment of design parameters. Due to the sensitivity of such tools, their adoption has the potential to deliver significant advantages to both the Contractor and Asset Owner – with the possibilities realised in terms of time efficiencies, costs, frequency of testing and, perhaps most importantly, reduced ongoing maintenance costs due to improved 'live' construction control that may help deliver a near-uniform product.

This paper presents – at an overview level – a number of tools that have been demonstrated to be effectively used as alternative methods of site assessment. The details in this paper are based on the experiences of the authors within Australian construction sites over the past eight (8) years, and identify both the advantages of using such tools and the current limitations that prevent their widespread acceptance across the earthworks industry.

2 KEY LIMITATIONS OF CURRENT ASSESSMENT TECHNIQUES

Due to required brevity, the review of commonly adopted assessment techniques within Australia has largely been limited to: (i) density testing – widely adopted for QA of achieved earthworks compaction); (ii) California Bearing Ratio (CBR) – typically used to assess quality of materials, subgrade treatment requirements and as a basis for a design (or achieved) modulus parameter; and (iii) Dynamic Cone Penetrometer (DCP) – typically used to infer bearing capacity or strength parameters.

The limitations associated with each technique can be largely categorised in terms of:

- *Reliance upon an unproven assumption* – that increased density or CBR measurement directly correlates with higher strength or modulus parameters. Previous research detailing how this assumption is not universal and how density-based regimes are inappropriate to validate the achieved engineering properties of compacted earthworks have been extensively cited in Mooney et. al. (2010) and Livneh & Livneh (2013). Similarly, Austroads (2009) cites previous research that concludes that CBR is not well correlated to, or an accurate predictor of, the modulus parameter.
- *Use of generic correlations* – required to be applied to transform results of index tests (density, CBR or DCP) into equivalent engineering parameters. Each step within a transformation process would be expected to introduce error, and which compound in the calculation of the desired parameter. For example, Austroads (2009) summarised previous research and concluded that variation within the generic CBR → Modulus transformation step alone would be expected to yield a modulus parameter that may be "100% to 300% higher or lower than expected" (due to the presence of the non-linear stress and strain dependent relationship of the modulus parameter).
- *Over-estimation of applicability / sensitivity of test technique* – Significant variation is known to be introduced within the source test result, due to equipment and operator error. Thus, 'repeatability' should always be considered when attempting to resolve subsequent parameters, such that the accuracy of the engineering parameter is not over-estimated or mis-represented. Examples of published test repeatability estimates – noting that such values aggregate material variability alongside measurement errors – for the DCP used in field testing would is considered to be approximately ±40% (e.g. Mellish et. al., 2014), whilst Rallings (2014) observed that within any material-specific CBR dataset, a single CBR value would exceed ±30% of the median CBR value 40% of the time. Similarly, Look (2019) identified issues with density tests not routinely having the oversize correction factor applied, resulting in results that did not accurately reflect the *insitu* condition. However, allowing for such magnitudes of 'repeatability' error does not appear to be habitually included when assessing the accuracy of subsequently derived parameters.
- *Applicable Test Depth* – Construction plant improvements (e.g. weight and compactive effort delivery method) since the development of typical density-based testing regimes now means the depth to which effective compaction is currently achieved is well beyond the 300 mm lift thickness limit included within typical Technical Specifications. Instead, the continued inclusion of the maximum thickness is largely due to the limitations of the equipment available for onsite (density) assessment; whereby the 'zone of influence' of the test (namely the depth of excavation for sand replacement or full extension of the nuclear density gauge probe) is limited to 300 mm.
- *Delay prior to test finalisation* – The time lag between fieldwork completion and test reports being finalised is significant, such that the results of routine QA assessment cannot be applied to improve the minimum standard or uniformity of the product (i.e. material is already well covered by the time QA test results become available).

3 ALTERNATIVE ASSESSMENT TOOLS

As an alternative to the commonly adopted test techniques critiqued within Section 2, three (3) tools that can be used to directly measure design parameters within compacted earthworks are presented herein, namely:

- *Light Falling Weight Deflectometer (LWD)* – a dynamic plate-based test capable of directly producing load vs. deformation curves (and thus *insitu* bearing capacity, strength and modulus parameters);
- *Borehole Shear Tester (BST)* – a field based direct shear test where, by shearing the sides of a small diameter borehole – the drained shear strength of *insitu* materials can be directly demonstrated; and
- *Variable Energy Dynamic Cone Penetrometer (PANDA Probe)* – a rod based, hand driven penetration test that measures imparted (variable) energy and cone penetration per hammer blow.

Summary details of each tool and recent Australian experience are provided in the following subsections. Details relating to each test method, data interpretation, and the international development and adoption of each tool have been extensively discussed previously in Lee, Lacey and Look (2017).

3.1 Light Falling Weight Deflectometer

The Light Falling Weight Deflectometer (LWD) is a dynamic plate load test in which a sliding mass is allowed to free fall to generate a load pulse which passes through a rigid plate and into the ground as a uniform stress. The instrumentation within various LWDs can include the presence of a load cell and utilises either velocity transducers or geophones to monitor the associated deflection of the ground below the rigid plate. The key elements of a typical LWD are presented in Figure 1(a).

As both force and deflection values are measured over the duration of the LWD's load pulse, the composite Young's Modulus (E_{LWD} or E_{vd}) over the zone of test influence – taken as between 1.3 and 1.5 times the plate diameter – can thus be derived by application of Boussinesq elastic half-space theory.

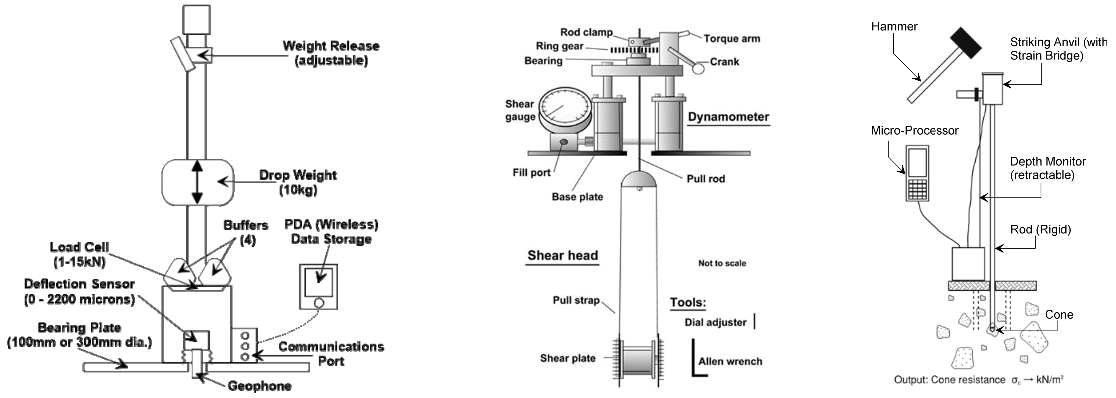

Figure 1. Sketches showing key elements of alternative test methods considered herein; (a) Light Falling Weight Deflectometer, LWD (sketch after Fleming et. al., 2007); (b) Borehole Shear Tester (BST); and (c) PANDA Probe

3.1.1 Advantages Offered by Innovation

As the LWD is a plate bearing test capable of monitoring ground deflection from an induced stress pulse, it has the ability to directly demonstrate the bearing capacity (allowable and ultimate) of a specific surface. Similarly, as the LWD is surface based, it can consider the behaviour of the subsurface materials present within the ‘zone of influence’ in the *insitu* (composite) state. The surface-based nature of the LWD also allows the *insitu* assessment of materials that include larger particles (e.g. rockfill) that would otherwise be considered ‘untestable’.

In addition, LWD’s fitted with a load cell offers a rapid method of constructing load versus deformation curves, analogous to the completion of a static Plate Load Test (PLT). Via the completion of LWD’s over a suitable range of test stresses, and the application of the general bearing capacity equation, LWD test results can be used to directly derive the *insitu* strength parameters (cohesion or angle of friction) present within the near-surface of the site the time of assessment.

3.1.2 Recent use of LWD within Australia as construction phase tool

Of the three (3) alternative test techniques presented the LWD tool is considered to be the easiest to use, offer the most versatility in terms of potential applications, and be the most frequently employed over the period of assessment.

Based on the author’s direct experience with the LWD over the past 8 years across QLD and NSW construction sites, the LWD has been proven to:

- Directly assess the bearing capacity, and thus provide or verify design parameters, of both cohesive and granular materials (e.g. for verification that design capacity of temporary works has been achieved).
- Be sensitive enough to demonstrate the modulus parameter improvement associated with the inclusion of geo-reinforcement products within a near-surface formation.
- Provide ‘near-instantaneous’ test results that facilitated the ongoing QA evaluation for rapid placement of granular backfill within significant excavations in time sensitive locations (e.g. during major motorway or rail track closures).
- Be used as a site characterisation technique to accurately map *insitu* modulus parameter variation across a site (validated in both road and rail projects, and by results of Intelligent Compaction (IC) enabled compaction plant).

Within the framework of a QA evaluation regime, the LWD’s evaluated by the authors have repeatedly provided an *insitu* modulus parameter that is strongly correlated to those derived from side-by-side PLT testing. Accordingly, confidence that the LWD can appropriately assess a stiffness parameter than can be directly related to the ‘reference’ field test technique has been repeatedly achieved (a result which density testing has not been able to consistently replicate).

Project- and material-specific alternative testing regimes that incorporated the LWD as the primary assessment tool have been accepted for earthworks QA for use within multiple major road infrastructure projects within QLD.

3.2 Borehole Shear Tester (BST)

The Iowa Borehole Shear Tester (BST) was developed in the 1960’s (Handy and Fox, 1967) and is a tool that can, for any soil type, determine the *insitu* drained friction angle and cohesion parameter. The tool effectively applies a shearing (uplift) force to the sides of a borehole, which is increased in steps until a peak shear strength is achieved. The BST is conceptually presented in Figure 1(b). The directly measured, *insitu* parameters arising from a BST are peak and residual (i) effective cohesion (c’) and (ii) angle of friction (ϕ').

3.2.1 Advantages Offered by Innovation

The BST is a unique technique for direct measurement of Mohr-Coulomb strength parameters within the *insitu* condition. A single test can be completed within an hour and thus, the BST offers a significant improvement over the (often-lengthy) turnaround time that is required for laboratory determination of the same direct-measured parameters. Similarly, the costs associated with obtaining undisturbed samples for such testing is also negated by the *insitu* measurement opportunity.

Typically, due to the unavailability of any equivalent test method with a reasonable turnaround, the *insitu* measurement of the effective cohesion and angle of friction parameters are not undertaken during the construction phase of project, even though the designer frequently adopts such parameters.

3.2.2 Recent use of BST within Australia as construction phase tool

The BST has been utilised by the authors at a major QLD infrastructure project between 2016 and 2018 to validate design parameters associated with large embankments were being achieved by the onsite compaction efforts being applied. A variety of compacted earth fill and rockfill materials were assessed via the BST testing undertaken.

Over 100 BST tests were undertaken upon various materials compacted from source materials comprised residual soil and highly weathered rocks – with the BST demonstrating a median effective angle of friction of 40, 42 and 43 degrees being achieved for compacted Siltstone, Sandstone and Basalt materials respectively. Within a high strength basalt rockfill that had a significant fines component, the BST was found to be suitably sensitive to demonstrated the achieved effective angle of friction was reduced to 37 degrees due to the presence of fines within the granular materials. For all sites assessed, the Coefficient of Variation (CoV) of between 7.5 and 10 % was observed.

Less repeatability of the measured effective cohesion (c') parameter was observed within the same tests – with a CoV of between 90 and 150% calculated from the completed tests. However, in all such cases, the BST was undertaken in predominately granular material.

3.3 Variable Energy Dynamic Cone Penetrometer (PANDA Probe)

The PANDA Probe – or Variable Energy Dynamic Cone Penetrometer – is an *insitu* test technique in which a cone is manually driven through a soil material (via hammer impacting upon a strain gauge anvil contained within the handle). For each hammer impact the probe records the variable driving energy and measures the resulting advancement of the cone. The general arrangement of the PANDA Probe is presented in Figure 1(c).

The applied energy and change in cone depth is combined to determine the soil resistance – reported as 'cone tip resistance, or q_d – as per details included in Lee, Lacey and Look (2017). The manufacturer (Sol Solution) of the PANDA instrument then documents the 'cone tip resistance' (q_d) parameter can then be interpreted analogously to the use of the Cone Resistance (Qc) profiles recorded by a Cone Penetration Test (CPT) – to infer relative density / consistency of the subsurface profile or to derive material parameter profiles (e.g. shear strength, angle of friction or modulus values).

3.3.1 Advantages Offered by Innovation

Used as an acceptable earthworks QA tool, the PANDA probe offers the ability to quickly profile the near-surface profile and, without further laboratory assessment, provide a test result that is suitable for direct use for engineering parameter interpretation – either by (i) using q_d as equivalent to Q_c or (ii) proving that within the near-surface profile, the material condition does not deteriorate with depth. Thus, in addition to speed of test (and results turnaround), the use of the PANDA Probe also offers a technique to increase the thickness of effective QA testing

In addition, due to the variable energy nature of the PANDA, whereby the imparted energy and cone penetration is measured for each hammer impact, the tool offers the advantage that energy input can be tailored to the strata being evaluated. This is especially relevant to soft materials, in which lower energy hammer impacts can be deliberately imparted in order to characterise the material layer. In comparison, the DCP uses a standard energy per hammer blow and thus does not have the ability for such material tailored variations to be adopted.

3.3.2 Recent use of PANDA within Australia as construction phase tool

The PANDA probe has been evaluated by the authors as an QA tool for earthworks compaction assessment on a number of major QLD and NSW infrastructure projects over the last 4 years. Based on project-specific trials, Technical Specifications that have been produced that incorporate the PANDA probe to (after initial correlation) both (i) increase the acceptable thickness of individual earthworks 'lifts' to a depth of 600 mm; and (ii) replace density testing to assess the material state within trench backfill for depths of up to 1,200 mm.

The basis of these project- and material-specific Technical Specifications for PANDA use has demonstrated that the 'Cone Tip Resistance' (q_d) can (for specific sites / materials) be correlated to *insitu* density test results and modulus parameters via relationships of sufficient strength and statistical significance that an equivalent Density Ratio (DR) can be demonstrated. This observation is largely in accordance with the manufacturer's recommendations and previous literature (e.g. Langton, 1999), although the q_d thresholds correlated to specific DR targets were found to be significantly increased from those previously published. It is further noted that the predictive models defined within recent Australian use have also incorporated the effect of the variation in observed compaction between the surface and 'critical depth', such that surface based density tests can be utilised for the original derivation of the material-specific correlations.

The 'repeatability' of the PANDA probe has been measured in direct comparison to side-by-side DCP testing – a recent QLD project evaluated both tools and found, based on 173 test results, that for any standard increment measure between 50 and 300mm, the PANDA probe and DCP test demonstrated similar variability, with the 80th percentile of repeated tests showing results that were +/-20% of the averaged value for both PANDA and DCP testing (q_d or mm/blow respectively).

However, the PANDA Probe suffers from the same limitation inherent to penetration test techniques; namely the effect of larger particles within the tested materials providing artificially inflated test results or premature test refusal. The observed advantage the PANDA Probe offers (over the DCP) in such ground conditions is both the PANDA's ongoing depth measurements – which allows for greater definition of the depth to, and thickness of (if penetrable) the larger sized particles – and the ability to impart greater test loadings via the PANDA than the (standardised) DCP hammer, such that the cone may penetrate particles and continue the test.

4 POTENTIAL ADVANTAGES OFFERED BY USE OF INNOVATIVE SITE ASSESSMENT TECHNIQUES

The limitations previously identified relating to the continued use of density testing for earthworks and near-surface QA are largely overcome by the use of one (or more) of the presented alternative test methods. In summary, the following advantages are offered by the use of any of such test techniques:

- *Speed (Fieldwork)* – The onsite duration of the alternative QA methods are comparatively quicker than those required for the completion of the field component of traditional density assessment. For example, a single LWD or PANDA Probe test can be completed in less than 5 minutes. Due to this speed of fieldwork, it is feasible that a higher frequency of testing could achieved whilst maintaining a similar onsite duration (i.e. increased test frequency for no net cost increase for onsite time).
- *Speed (Turnaround of Results)* – The results of the alternative QA methods presented are all available near-instantaneously. In comparison, the turnaround period for traditional density assessment is measured in days, whilst laboratory shear tests require multiple weeks.
- *Increase the thickness of QA Testing* – Limitations to the allowable lift thickness are currently driven by depth limitations in QA of compacted material. The use of any of the proposed alternative QA methods extend the achieved depth of assessment and, if two such methods were coupled (e.g. LWD and PANDA Probe) then achieved depth of assessment could exceed the depth of effective compaction – thus allowing a more efficient use of plant capabilities, a significant cost and scheduling savings for the project, whilst presenting no additional risk to Asset Owner.
- *Direct Measurement of Design Parameters* – All of the alternative test techniques presented herein allow direct assessment of design material parameters being achieved *insitu*, negating the need for assumed relationships or generic correlations to be utilised during back-calculation of likely achieved parameters. Direct measurement of design parameters, and variation thereof, may also potentially reduce the associated 'Consumer Risk'.
- *Accuracy and Quantification of Variability* – As the alternative test techniques allow direct measurement of parameters, they also facilitate the direct assessment of the variability of the *insitu* parameters being achieved across the site. In comparison, traditional density testing should be considered precise, but not accurate.
- *Adaptability of Test Variables* – The test techniques are fully adaptable such that each test type can be tailed to replicate specific conditions (e.g. stress magnitude applied). This means that the *insitu* condition / material response under design loading conditions can be directly assessed and such loading conditions can be altered as one moves towards / away from the final trafficable surface
- *Used to Influence Construction Methodology* – Due to the speed of test and availability of results, the use of the proposed alternative test methods, specifically the LWD and PANDA Probe, can provide 'live' feedback to the state of materials at the time of test. Thus the alternative test methods can be used to provide 'live' guidance to provide both a superior (uniform) product to the Client and facilitate more efficient use of construction plant / resources for the Contractor (in order to achieve specification requirements).
- *Direct Linkage to Intelligent Compaction Measurements (allowing for 3rd Party Testing)* – As Intelligent Compaction (IC) is set to become more prevalent throughout Australia, suitable independent test methods must also be developed for verification purposes. Density based test regimes should not be considered suitable for such works, due to the lack of a consistent relationship with the modulus parameter. Simple tools that facilitate direct measurement of achieved *insitu* stiffness and strength parameters – e.g. LWD or BST – would be suitable techniques for such independent verification of IC test results.

5 CURRENT LIMITATIONS TO WIDESPREAD ACCEPTANCE

Although alternative test procedures offer considerable benefits to both the Asset Owner and Contractor if adopted for construction phase QA regimes, there remains a number of significant impediments that prevent their widespread adoption within the Australian industry. Barriers exist both within the traditional framework of Technical Specifications and by the nature of the products currently available for use. Identified major limitations include:

- *Requirement to demonstrate relationship between results of alternative and traditional test methods* – Although a number of recent technical specifications include the potential allowance of alternative test methods for material assessment (e.g. TMR, 2018; Drechler et. al., 2019), there remains a requirement that the suitability of such alternative test method be validated to the *status quo* regime. However, this requirement to produce a consistent, high strength correlation between the strength or modulus parameter being measured *insitu* to the results of density testing is misplaced as it fundamentally assumes the density test result is the correct 'reference' value against which all others can be validated. This requirement places a significant barrier to adoption of non-density-based assessment techniques as it fundamentally relies on the existence of questionable (and likely variable) relationships for both of the correlation steps required.

- *No clear definition of 'acceptableness' for implementation of alternative test technique* – Notwithstanding the issues regarding the need for a demonstratable correlation with density test results, there also is a lack of a definition of what an 'acceptable' relationship is. Current Australian terminology relating to this aspect is limited, and largely requires a relationship that is "acceptable" in the opinion of the Administrator. This criterion is obviously opaque, and has the potential to be clouded by a variety of other factors. In comparison, similar international standards have clear, statistically verifiable measures to prove acceptance – for example, Highways England (2009) define that LWDs may be used for QA purposes as long as a linear regression coefficient (R^2) between the i*nsitu* modulus reported by the LWD and other 'reference' modulus measurement (PLT / FWD) is 0.45 or greater.
- *Lack of Australian Standard & Standardisation of Test Technique* – Currently, no relevant Australian Standard document currently exist for any of the alternative test methods detailed herein. Although international methods do exist, some review and update to these documents is required to reflect the Australian condition and likely intent of the test for use during construction phase testing. This would include the standardisation of variables associated with the test equipment itself (e.g. acceptance limits for LWD deflection magnitudes or the PANDA q_d), details to be provided on all test certificates and method for interpretation, such that a standardised parameter can be reported.
- *Configuration and Brand variability* – Further to the issue with lack of standardisation, the LWD further suffers from the multitude of brands and equipment variables that can be adopted for testing (e.g. plate diameter, test stress, location and type of senor used for deflection measurement). Thus, the 'standardised' stiffness parameters arising from similar field use of specific LWD's may vary between brands. Although all such variation is fully traceable to the experienced user, the apparent variability in the reported *insitu* modulus parameter can be viewed as an additional reason for the 'unreliability' of the LWD instrument. Accordingly, the importance of detailing the specific set-up for LWD's to be adopted for *insitu* material evaluation within any specification needs to be recognised.

6 CONCLUSIONS

Three (3) tools suitable for use as viable alternatives to traditional assessment techniques (density, CBR or DCP) are presented herein. Based on the Australian research and evaluations completed to date, their use has the potential to overcome a number of limitations associated with traditional testing especially in a QA / QC context, and deliver major efficiencies and benefits to both Contractor and Client without significant change to the current (accepted) risk profile. However, a number of major limitations remain within traditional earthworks Technical Specifications that prevent their widespread Australian adoption as an effective construction phase tools, and from cost and time benefits being fully realised.

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