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Precision measurements constrain the implementation of more accurate testing in earthworks quality assurance

Les mesures de précision limitent la mise en œuvre de tests plus précis dans l'assurance qualité des travaux de terrassement

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ABSTRACT: Density was selected as the key Quality control (QC) parameter as its high precision was recognized in the early days. Precision in QC was chosen in favour of more relevant but difficult to measure parameters at the time. Precision is not the same as accuracy. As dry density ratio (DDR) index is now fully embedded in QC, one may mistakenly think that the factors measured are the key factors. DDR was intended to be just part of the decision-making process of quality and verification of the design requirements. On projects which use end product specifications, a DDR value then becomes THE de facto decision on pass / fail. This simplifies the site decision in having assessment metronomically stated. Because traditionally industry did not or cannot measure something should not diminish its importance. Several in-situ devices have been available for the past two decades and various research has shown the benefits. Data was acquired as part of field trials over multiple "live" projects. Conventional QC testing was supplemented with other field strength and modulus tests. Correlating to established DDR tests is blind to the influences of other factors influencing strength and modulus. Such tests measure a combination of underlying material, material quality, moisture content and density. A 95% DDR does not have a singular strength or modulus value as measured with one-to-one correlated testing as this is governed by material type.

RÉSUMÉ: La densité a été choisie comme paramètre clé du contrôle de la qualité (CQ), car sa haute précision a été reconnue dès les premiers jours. La précision en CQ a été choisie au profit de paramètres plus pertinents mais difficiles à mesurer à l'époque. La précision n'est pas la même chose que l'exactitude. Comme l'indice de rapport de densité sèche (DDR) est maintenant entièrement intégré dans le contrôle qualité, on peut penser à tort que les facteurs mesurés sont les facteurs clés. Le DDR devait n'être qu'une partie du processus décisionnel de qualité et de vérification de la conception. Sur les projets qui utilisent des spécifications de produit final, une valeur DDR devient alors LA décision de facto sur la réussite / l'échec. Cela simplifie la décision du site en ayant l'évaluation métronomiquement énoncée. Le fait que, traditionnellement, l'industrie ne mesurait pas ou ne pouvait pas mesurer quelque chose ne devrait pas en diminuer l'importance. Plusieurs dispositifs in situ ont été disponibles au cours des deux dernières décennies et diverses recherches ont montré les avantages. Les données ont été acquises dans le cadre d'essais sur le terrain dans le cadre de plusieurs projets « en direct ». Les essais de contrôle qualité conventionnels ont été complétés par d'autres essais d'intensité de champ et de module. La corrélation avec les tests DDR établis est aveugle à l'influence d'autres facteurs influençant la résistance et le module. Ces tests mesurent une combinaison du matériau sous-jacent, de la qualité du matériau, de la teneur en humidité et de la densité. Un DDR à 95% n'a pas de valeur de résistance ou de module unique, telle que mesurée par des tests corrélés un à un, car elle est régie par le type de matériau.

Keywords: Dry density ratio; precision; accuracy; quality control; earthworks; Modulus; CBR.

1 INTRODUCTION

The aim of compaction is to reduce the air voids, and with many associated gains such as strength, reduction of permeability, reduced settlement, etc. The use of maximum dry density (MDD), optimum moisture content (OMC), dry density ratio (DDR) and California Bearing Ratio (CBR) originated from studies completed in the 1930s and standardised by the 1960s. The DDR compares the field dry density to the laboratory MDD.

The standard density test has revolutionized construction testing, enabling engineers to assess and control soil compaction in a consistent manner. DDR has been used successfully as density tests are very precise. Precision is not the same as accuracy, which is closeness to a "true" value, while precision is the closeness of the measurement to each other.

Look (2018) showed that DDR is very precise but is not very accurate. Conversely, the plate load is (PLT) is accurate, but not very precise. Such findings were also apparent when adopting DDR as the defacto standard as a quality QC measurement. The decision on pass / fail can then be simply applied to the site decision making process in having your daily assessment activities metronomically stated. This may create a false confidence in the design and construction process when precision is not the same as accuracy.

Engineers assume a direct relation between density and strength or modulus (i.e., the greater the density achieved, the higher the strength or modulus of the compacted material). However, the peak CBR does not necessarily occur at the MDD. Seed and Chan (1959) had shown the peak strength is lower at the MDD due to the lower moisture content even when the density is lower (Figure 1 from Leroueil and Hight, 2013).

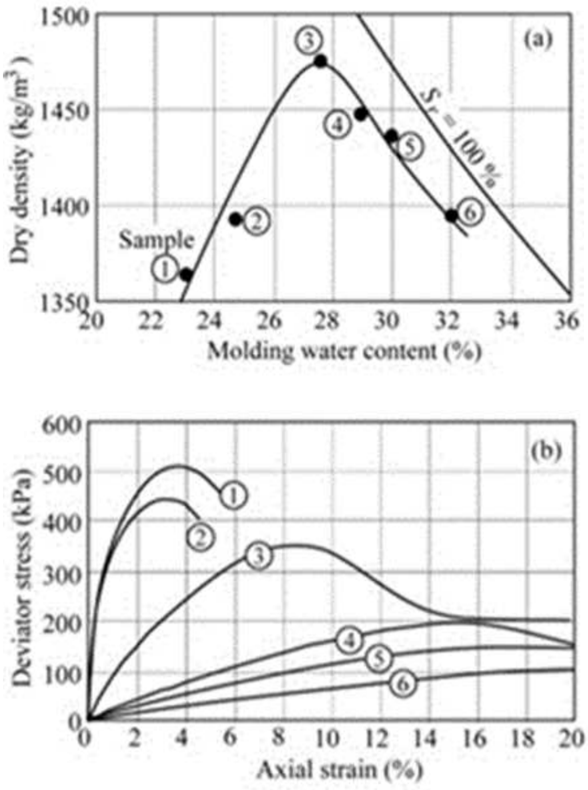

Figure 1. (a) Influence of moulding water content on the dry density and (b) stress-strain relationships.

Several in-situ devices have been available to industry for the past two decades with many benefits being constrained by correlations to DDR. Nazarian and Correia (2009) show the field modulus is highly dependent on the moisture content (Figure 2). Drying or wetting after compaction can significantly influence the modulus result. A minor change in moisture content results in 6% change in density, but 300% change in modulus. Most of these modulus values still satisfy a 95% MDD criteria – but at a different moisture content.

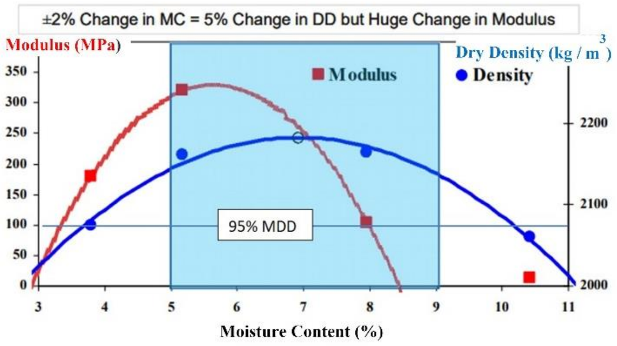

Figure 2. Impact of moisture on density and modulus.

2 HISTORICAL DDR AND CBR IN QC

2.1 Past decisions with present considerations

Figure 3 shows a retrospective decision process using a force field analysis to arrive at accepting DDR in QC testing. This approach is used as a decision-making tool. It compares the forces that are either driving the movement toward a decision or goal (helping forces) as compared to the factors blocking the movement towards that goal or decision (hindering forces).

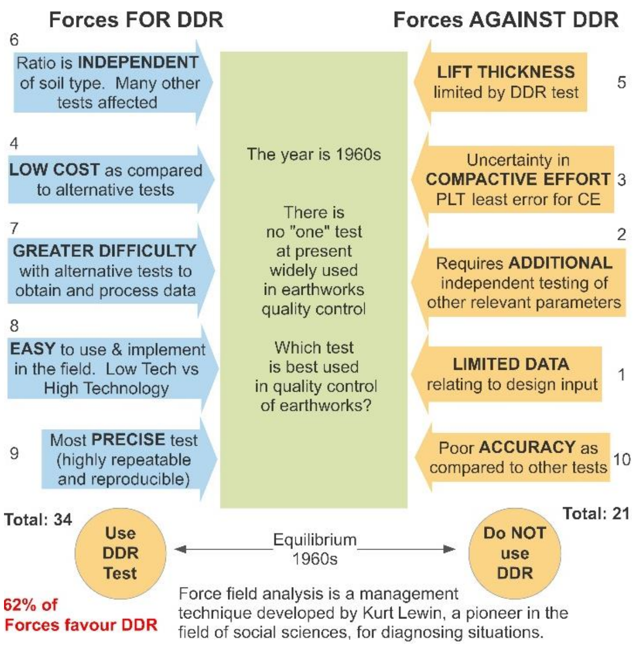

Figure 3. Force field analysis decision to use DDR as the main QC parameter in the 1960s. 10 is most desirable.

Adopting DDR as the main QC parameter far outweighs the negative considerations. High precision, ease of use, and greater difficult of technology of the tine outweigh negative considerations of accuracy. Thus, using DDR was logical choice in the 1960s based on the technology of the time.

Figure 4 uses the similar considerations in the decision to use DDR as the main QC parameter in the

2020s but updated for current technology. The decision is now weighted against using DDR given current technology in current times.

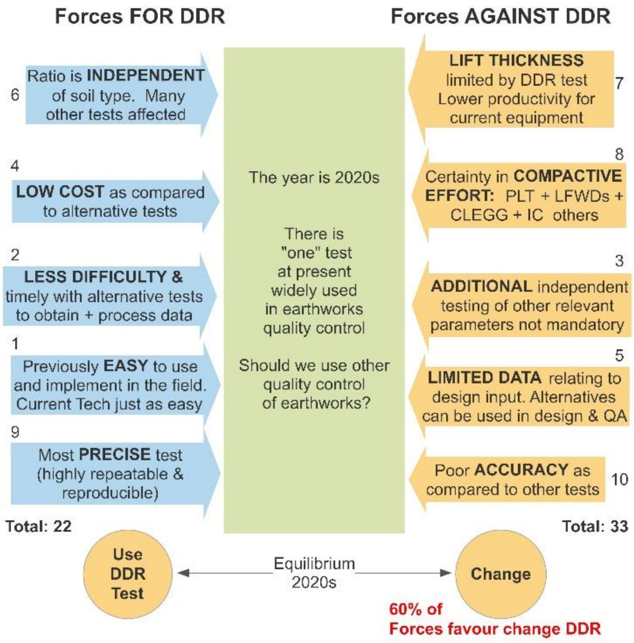

Figure 4. Force field analysis decision to NOT use DDR in the 2020s using similar considerations as the 1960s.

2.2 Historical testing and compaction history

The CBR test was developed to assess the load-bearing capacity of soils. In modern times it is used to correlate with resilient modulus.

A heavier compaction roller can achieve greater compaction energy and soil density. Early machines prior to 1900 were 6 tons but increased to 10 to 12 tons by the time the compaction test in the 1930s, and 15–20 tons in the 1940s by the time the modified compaction test was introduced.

During the early standardisation of tests (1950s) the development of smooth drum vibratory compaction rollers further improved compaction efficiency, with machine around 20-25 tons. By the 1990s, advances in engineering and construction materials allowed for larger compaction rollers with typical weights of 30-35 tons. High-frequency vibratory compaction rollers from 2000, and sophisticated control systems has led to larger and heavier models weighing over 40 tons.

Vehicles weights also changed over the years. However, it is truck axle loads that governs road performance. The average truck axle load was around 2.5t in the 1920s and increased to approximately 8.5t by the 1980s with technological in truck design.

3 COMPARSION OF TESTS

3.1 Early days to assess benefits of tests

In the symposium on compaction of earthworks and granular bases, Selig and Truesdale (1967) examined various testing devices for various factors affecting compaction. They found density has a low variability compared to other tests. Thus, precision took preference over the more useful but wider variability of other measurements of the time.

3.2 Current tests and benefits

A survey of engineers ranking what attributes are desirable in a test equipment showed that accuracy is the preferred attribute (Look, 2018). The ranking order for the 8 attributes of a test equipment was:

1. Accuracy; 2. Precision
3. Time to conduct test / Ease of use
4. Time to process results / Ease to process & report
5. Amount of data obtained / Cost of equipment

Field trials were used to benchmark the various alternative equipment and compared with traditional DDR measurements for various sites (Table 1).

Table 1. COV for various tests considered over 5 sites.

Test	Coefficient of Variation (%)		
	Median	Low	High
Density Ratio	2.0	1.8	2.9
Geogauge	26.5	19.1	34.5
Prima LFWD	33.5	15.0	35.7
CBR	40	17.0	58
Zorn LFWD	34.1	21.6	51
Clegg	36.0	26.0	54
PANDA			
(50 – 100mm)	53	34	74
(150 – 200mm)	50	48	92
DCP			
(50 – 100mm)	38.0	28	97
(150 – 200mm)	53	34	74
Plate Load Test	77	14	142

The lot coefficient of variation (COV = standard deviation / mean) at each site was used to judge the precision, and the DDR test is the standout leader (COV < 3.0%), with the Plate Load test (PLT), the most variable as compared to other tests.

However, precision is the 2nd preference attribute as compared to accuracy. Accuracy was assessed in terms of how well the results compared with each other for similar order of the high to the low values for the various test sites. The PLT was the most accurate, but is the least precise test (Look, 2018).

4 DISCUSSION

Density has historically satisfied a 1 parameter need in QC assessment. Other quality parameters are assessed independently. A 95% DDR does not have a singular strength or modulus value – although this is an implicit assumption (Table 2). This is not rock fill testing as all materials conform to "soil" after compaction.

Table 2. Modulus and strength at 95% DDR (Look, 2021).

Fill Material Origin	PLT E_{V2} (MPa)	In situ angle of friction φ (°)	
		Smooth	Padfoot
Sandstone	70	45	45
Interbedded Siltstone/Sandstone	40	41	39
Basalt	65	39	43

When field supervisors ask for a correlation of modulus to provide a linkage with DDR as the de facto standard, a poor correlation often results. This is due to different zones of influence, modulus being affected by several factors (not just DDR), and the DDR having a normal probability density function (PDF) and other tests having a non-normal PDF. Look (2021) show a methodology to avoid such correction inconsistencies

LFWD results (Figure 5) show that both Type I and Type II errors are occurring when DDR is compared with LFWD data. A Type I error is the incorrect rejection of a true null hypothesis. Type II error is the failure to reject a false null hypothesis. A direct paired correlation had 20% "errors" in its assessment.

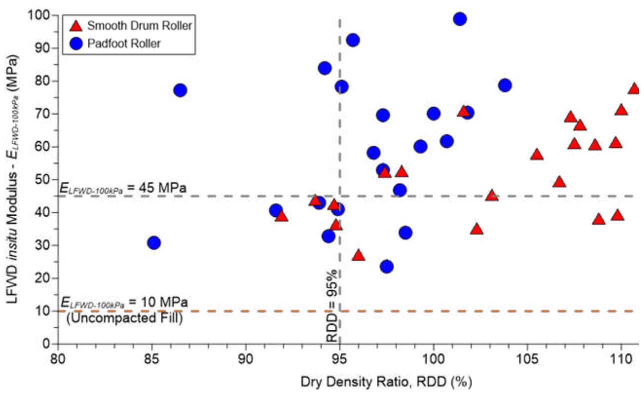

Figure 5. LFWDs correlated to density ratio of compaction for sandstone material.

Riad et al. (2023) review various testing equipment in compaction QC in the U.S. Curently, 93.5% of state agencies use density specifications rather than modulus based compaction controls. Similarly, in Australia, modulus based compaction levels are curently the exception. A requirement on parallel testing with DDR leads to additional cost and time.

5 CONCLUSIONS

Modern pavement designs are based on modulus and strength values. When such measurements are correlated to QC density testing, a poor correlation often results as this is a multivariate relationship.

Traditional QC testing density has focused on its key benefit of precision and simplicity without appreciating the poor accuracy associated with this measurement. The decision is between the past comforts and success of using density measurements vs the technical benefits of modern testing equipment. The early benefits of using DDR now seem to impede what should be possible given current technologies.

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