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DYNAMIC PROBING (DPSH) INVESTIGATION FOR EMBANKMENTS AND BACK-FILL IN SEQUENTIAL EXTRACTIVE LAND USE

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ABSTRACT: Extractive land use, such as quarrying for construction materials, is typically progressed by excavating pits, constructing bridging embankments, and back-filling pits with overburdened or processed waste materials. Collection of geotechnical data at various stages of the extraction and back-filling activities can provide a valuable record of the history of the ground conditions and provide input to the assessment of land use options when back-filling is complete. A mechanized dynamic probe in the super heavy category (DPSH) has been used in recent investigations as the primary tool for geotechnical data collection in these rapidly changing environments. In addition, data from a combination of lightweight manual dynamic probes (DCP), cone penetration testing (CPT), standard penetration testing (SPT), and installed settlement plates have been collected, allowing a comparison of the methods. The condition of embankments formed on the batter of open pits and temporary embankments forming land bridges between pits can be effectively assessed using these techniques. Backfill of pits with site materials or with imported material should be progressively monitored and assessed for suitability and/or ground improvement requirements for future land uses.

Keywords: Dynamic probing, Sequential land use, Extractive resources, Embankments

1. INTRODUCTION

The extraction of naturally occurring materials for construction or for the separation of valuable commodities is an important process in most economies [1]. During the extraction process, unwanted material can be returned to the excavated pits. This back-filled material can be unwanted materials near the surface (overburden) or fractions of the material separated by some processes such as washing and screening. Where necessary, material may be brought to the site to add to the backfill. Typically, lakes with distinctive environmental conditions [2,3] remain in the partially back-filled pits.

In Australia, extractive sites operate under an approved rehabilitation plan, which outlines the final land condition and anticipated future land use for the site. Sequential extractive land use is a term for “utilizing land sequentially, enabling land to be used later for another purpose once the current land use has ended or been terminated” [4].

An example of some stages that may occur in extraction and back-filling at a site can be observed at Batson’s Sand and Gravel quarry, New South Wales. This site was studied by one of the current authors while in operation in the 1990s [5]. The site has been operated and backfilled and returned to a natural condition over the succeeding decades (Fig.1). The dams used for water management during operation have been retained in the final landform as lakes.

Sand and gravel extraction is distinctive in that the resource materials are typically near the surface and relatively continuous laterally [6]. The operational pits are expanded as the resource is extracted. If a zone of natural ground is left as a barrier between adjacent pits, this can be referred to as a landbridge. Where excavation expands, an embankment can be constructed to separate the expanded pit into separate pits by constructing dikes (or dykes), otherwise known as in-pit embankments.

Separate pits are required in many extractive resource operations to manage water. This is required both in operations excavated by dredging and those excavated by dry mining methods. For dredging, the water level needs to be maintained to optimize the reach of the dredge. For dry mining, which may be done by the use of dozers, excavators, and scrapers, excavation below the water table requires a nearby location to dispose of water pumped from the ground or from in-pit sumps.

Unwanted fine materials, known as slimes, can accumulate at the base of pits where turbid water is returned to a pit from a processing plant. Accumulated slimes can deleteriously impact the long-term settlement characteristics of the site. Overburden materials can be placed as batters in existing pits to improve stability and reduce water inflow while minimizing material handling.

These various site activities result in a site with a complex range of depths and types of backfill. A

Fig. 1 Example of some stages that may occur in extraction and back-filling. Batson's Sand and Gravel quarry, northern New South Wales

schematic example is illustrated in Fig. 2. It is evident that maintaining a record of the backfill materials and compaction during filling provides an important record of the likely settlement characteristics of the ground and its suitability for future land use options.

A review of research into DPSH applications has been presented elsewhere by the authors [7]. Other recent articles on DPSH include a study on ground improvement assessment [8] and pile-bearing capacity [9]. Penetrometers have been applied to assess the compaction of mine waste and the progressive breakdown of backfilled waste rock [10,11]. MacRobert and Stergianos [12] have also presented an updated review of their extensive database related to identifying competent ground conditions with DPSH.

This paper outlines some of the ways in which the condition of the constructed embankments and backfill can be progressively monitored for compaction and stability. In particular, the use of the dynamic penetrometer super heavy (DPSH) is described together with its potential correlation with other investigation methods. In particular, it is shown that simple direct correlations of large data sets cannot achieve a simple correlation result because of the 'differential refusal' for each investigation tool.

2. RESEARCH SIGNIFICANCE

The study collates examples of dynamic probing in the context of backfilled pits and related landforms. An improved understanding of how to assess such rehabilitated lands will assist in the management of land use and in avoiding hazards such as excessive settlements that can occur when backfill is inadequately compacted. The study provides insights into the potential correlations between sub-surface investigation tools in a range of material types. Such correlations are required for the future development of standards and regulations in the field of land reclamation.

3. COMPACTION VERIFICATION

In the course of providing verification of the backfill compaction of various quarries, CMW Geosciences have utilized a range of methods, including Dynamic Cone Penetrometer (DCP), Cone Penetration Test (CPT), Standard Penetration testing (SPT) and Dynamic Penetrometer Super Heavy (DPSH).

The DPSH-B utilizes a 63 kg weight dropped through 750 mm. The cone has an effective area of 20 cm^2 with a 90^o cone angle (Fig. 3A). In Australia, the DCP utilizes a 9 kg weight dropped through 510 mm. The DCP cone has a diameter of 20 mm with a 30^o cone angle (Fig. 3B, Australian Standard AS

1289.6.3.2 [13] and other standards [14]). Other comparable dynamic cone systems have cone angles of 60º (e.g. ASTM D6951-03 [15,16]) or 90º (e.g. DPL, EN ISO 2005. 22476-2 2005 [17]). Table 1 summarizes the two main cone types and shapes referred to in this study.

In one case of back-filling of a quarry, DPSH probes were performed at various times during the accumulation of a clayey back-fill. Fig. 4 shows the DPSH probe records at two points in time, separated by approximately 18 months. During that time, approximately 5 m of fill was also placed in the area.

The initial probing (Fig. 4A) shows the effect of the placement of thick layers of 1-2 m in thickness with incidental compaction by the movement of the dump trucks and other equipment. The intervals of low penetration per blow indicate the well-compacted surfaces, whereas the intervals of high penetration per blow indicate less compacted material.

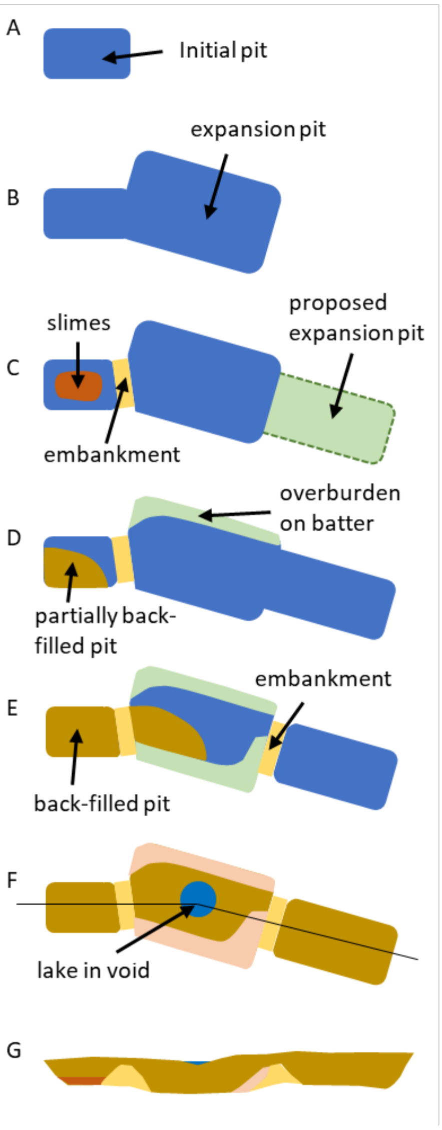

Fig. 2 Illustration of some stages that may occur in extraction and back-filling. A-F: plan view. G: cross-section of stage F

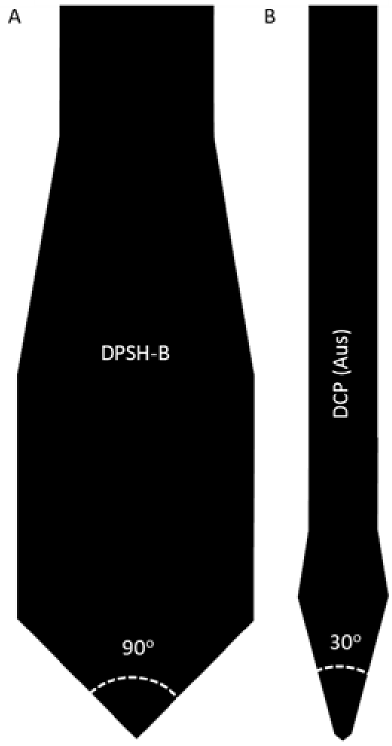

Fig. 3 Illustration of the (A) DPSH and (B) DCP (Australian) dynamic cone heads and shafts to relative scale

Table 1 Summary of the common penetration cone head shapes. Aus. is Australian Standard AS 1289.6.3.2

Tool	Cone diam. (mm)	Cone area (cm^2)	Cone angle (º)
DPSH-B	51	20	90
DCP (Aus)	20	3.1	30
CPT normal	36	10	60
CPT heavy duty	44.1	15	60

The later probing (Fig. 4B) shows the effect of additional placed fill and self-weight compaction. In particular, the material classified as soft has moved toward the firm and stiff categories.

For a quantitative comparison, the upper 1 m of the overlapping probes has not been included so as not to be influenced by the difference that may be related to a free surface in the previous case. The penetration per blow is seen to decrease by 10% in the upper part of the backfill and 22% in the lower part of the backfill (Table 2). The observed relationship is consistent with the self-weight of the backfill being a significant contributor to the compact of the fill over time.

During the time between DPSH probing, settlement plates were installed to record the ongoing settlement as fill continued to be placed at the site (Fig. 5).

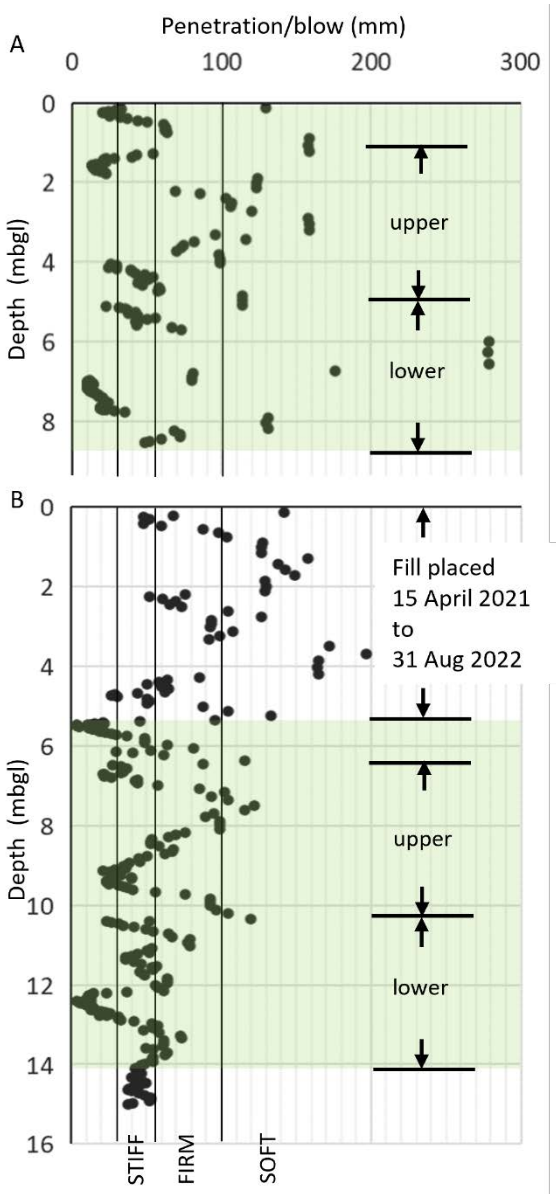

Fig. 4 Graphs of DPSH penetration per blow values (A) before and (B) after placement of approximately 5 m of fill. Shaded area shows the interval of overlap of the before and after probes separated into arbitrary upper and lower zones for comparison in Table 2

4. CORRELATIONS

There have been numerous attempts to correlate different penetration tests. Correlations are summarized elsewhere [18] and vary widely as the effect of differing cone shapes and other variables such as the energy input, makes the outcomes of the correlations highly complex. Such correlations typically acknowledge that different material types.

Table 2 Summary of the DPSH penetration per blow values from Fig. 4

Overlap interval	Before: Average Penetration /blow (mm)	After: Average Penetration /blow (mm)	Percent reduced (%)
Upper	61	55	10
Lower	46	36	22

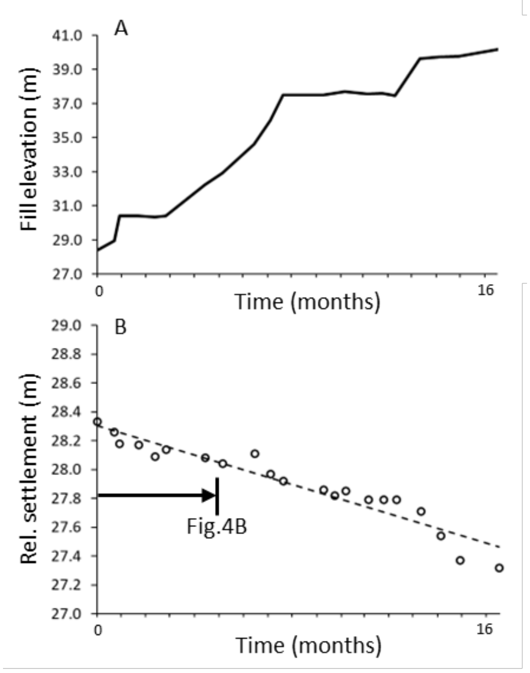

Fig. 5 Graphs of fill history and settlement (subsequent to settlement plate installation) at the site of Fig. 4

Such as clays and sands require different correlations. Attempts at correlation typically to not acknowledge that it is also necessary to appreciate the characteristics of different tools to recognize when correlation is optimal. One of the characteristics of penetration tools is that they undergo refusal when the material they encounter becomes too resistant. Therefore, the penetration versus resistance relationships of the tools is non-linear on differing scales.

Refusal is represented by reaching a threshold value (20 blows per 100 mm penetration for DCP) such that penetration effectively ceases. Different penetration tools have different refusal depths for the same soil profile.

Lighter-weight penetrometers will typically undergo refusal before a more heavy-duty penetrometer. Lighter-weight tools such as DCP typically encounter refusal (11 out of 25 tests in Fig.

6) compared to heavier-weight tools such as DPSH (no refusal, 2 tests exceeded 20 blows for 100 mm) as illustrated on a compilation of data at a site with clayey and sandy clay soils (Fig. 6).

Given the typical relationship illustrated in Fig. 6, the correlation between tools could be achieved in the zone where both tools have a good sensitivity to changes in soil strength. However, if a correlation attempts to include conditions where one of the tools is approaching refusal, then the correlation quality would be expected to decrease significantly.

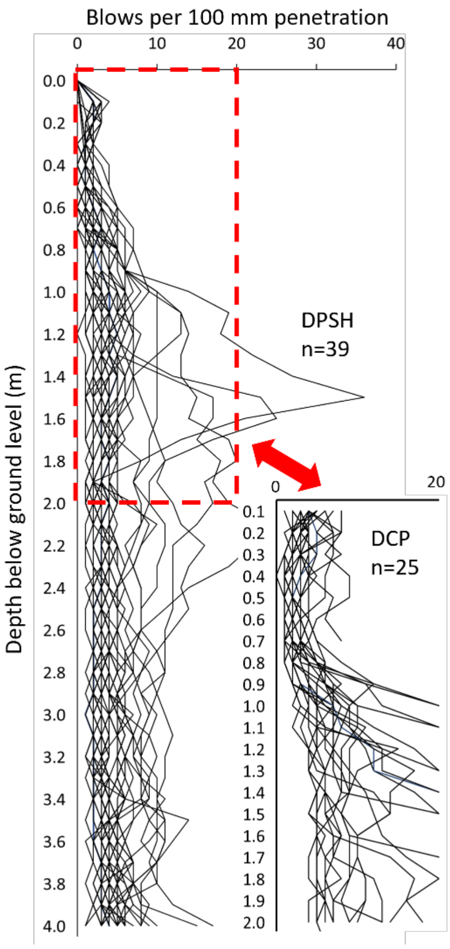

Fig. 6 Illustration of the influence of refusal on the correlation of penetration tools

4.1 An Example in Sand

An example of a correlation of DCP and DPSH is provided from an investigation of coastal sand deposits in eastern Victoria, Australia. The sands are predominantly quartz with minor shell components. DPSH was used as the primary tool for the investigation of ground conditions. Where access was especially restricted for environmental reasons, DCP was conducted. Both tools were used at one location to assist with correlation. At this location, the data represented as DPSH 1 and DCP 1 was collected (Fig. 7). When represented by the same parameter (N_{10}), DPSH 1 and DCP 1 show generally consistent parallel trends until the DCP was stopped at a target depth of 4 m.

In contrast, DCP 2, located in a nearby area, encountered refusal at about 3 m. The quality of the correlations between each DCP and the DPSH can be assessed as the ratio of each DCP to the DPSH according to the number of blows for each 0.1 m of penetration. As seen in Fig. 7, DCP 1 and DPSH 1 correlate well in terms of the shape of the penetration record, with the DCP having approximately twice the number of blows for a given penetration distance. In contrast, DCP 2 and DPSH 1 have poor correlation, especially as DCP 2 blows per penetration depth rises sharply at 2 m, where it enters high resistance and approaches refusal. The DPSH 1 blows per penetration depth also rises in response to the higher density sands encountered in this zone, but refusal is not encountered. Clearly, where refusal characteristics are not considered, the empirical correlation of these tools cannot be expected to provide a consistent result even in similar materials.

4.2 An Example in Clay

An in-pit embankment constructed of clay overburden in a construction sand deposit was investigated using DPSH, CPT, and DCP methods. The relationship between DPSH and CPT was shown to correlate closely [7].

An example of the relationship between DPSH and DCP in the same embankment is shown in Fig. 8. One notable feature is that, unlike the example from sand, the DPSH blows per 100 mm (written either as N(10) or N_{10}) is greater than for DCP in the clay material. It is also observed that the DPSH N_{10} increases progressively throughout the probing, whereas the DCP shows relatively consistent values for the first 1.5 m. Both DCP records meet refusal at about 3.2-3.3 m, coinciding with an increase in N_{10} value recorded by the DPSH. The local increases in DCP values are inferred to represent the more compacted surfaces of the embankment construction stages.

The fundamental differences between the DPSH and DCP records in the clay embankment are inferred to be a function of the different cone head shapes. The flatter (90°) cone angle of the DPSH may produce more compressive stress in the soil in comparison to the sharper (30°) cone angle of the DCP, which may undergo more shear on the cone face while producing less compressive stress at the tip. This interpretation is based on the understanding that clay materials may increase in compressive stress with greater confinement while the shear stress can remain constant [18].

4.3 Correlation Overview

It is common for engineering descriptions of soils, including the Australian Standard [19], to define descriptive terms and allocate them abbreviation codes to assist in recording information about soil behavior, in particular strength. These descriptions are usually separated according to the granular nature of sandy soils and the cohesive nature of clay soils (Table 3).

The Australian Standard definition of these terms is shown in Table 4 and Table 5, although it is noted that the terms may be defined differently in different standards and sources [e.g. 20].

The purpose of Table 4 and Table 5 is to present the authors' current understanding of the current time with reference to specific published sources. It is anticipated that correlation from site to site and for complex soil types will vary and that understanding of these factors will develop further with additional research.

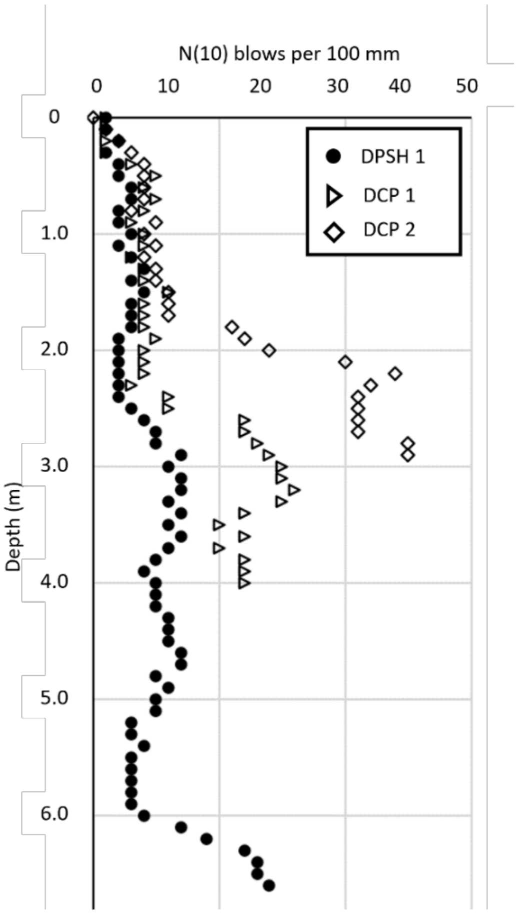

Fig. 7 Graph of one DPSH and two DCP field tests in sand. DCP 1 terminated at the target depth, and DCP 2 met refusal. Full depth of DPSH 1 is not shown

It is noted in Tables 3 and 4 that the defined ranges from the Standard carefully distinguish between values less than or greater than and those also equal to the values so that an unambiguous classification is presented. The same approach is not recommended for the N_{10} values. The ranges are deliberately presented with a shared boundary value to allow for judgment in cases where data is close to or overlapping a boundary value. It is not intended that the N_{10} ranges provided are considered to be strictly applied but rather to be a guide to be considered alongside other data, such as field observations of materials and comparison with data obtained from other investigative methods.

In Table 4, the highest density classes have not been distinguished as the DPSH method appears to have low resolution in that range. Similarly, in Table 5, the lowest strength classes have not been distinguished, as the DPSH method appears to have low resolution in that range.

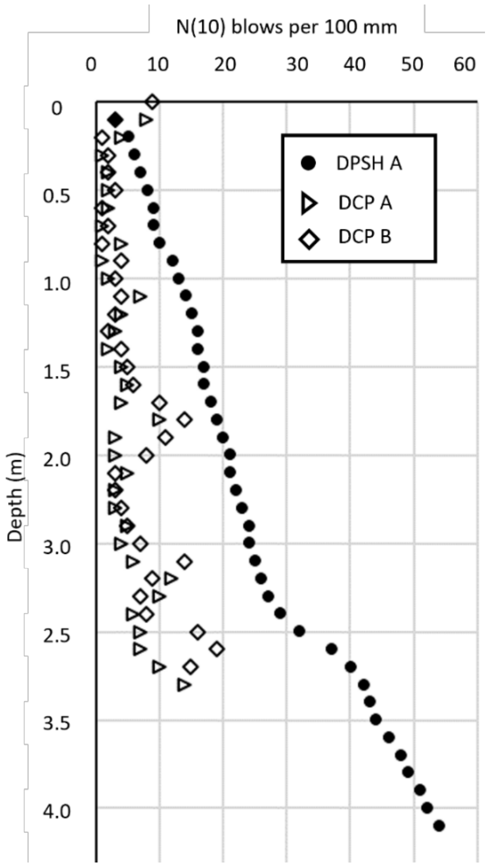

Fig. 8 Graph of one DPSH and two DCP field tests in a constructed clay batter. DCP A and DCP B were terminated at refusal. Full depth of DPSH A is not shown.

In general, the correlations proposed in Table 4 and Table 5 must be applied with an understanding of the sensitivity range of the DPSH instrument and an awareness of the confounding effects of progressive refusal of the tool.

A friction angle range has been included in Table 4. The friction angle values are intended as a very broad guide based on the relative density categories not directly from the N_{10} values.

In Table 4, the MD-D boundary has been selected at N_{10} of 20 blows following [21], although it is noted the same author has proposed this boundary be adjusted upward to 27 blows [12].

Table 3: Soil terminology codes

Type	Code	Description
Sand	VL	Very loose
	L	Loose
	MD	Medium dense
	D	Dense
	VD	Very dense
Clay	VS	Very soft
	S	Soft
	F	Firm
	St	Stiff
	VSt	Very stiff
	H	Hard

Note: The units and ranges of these properties are defined in Tables 4 and 5.

Table 4: Proposed DPSH correlations for sand

DPSH N_{10}	Relative Density	Range (%)	Friction angle (°)
<1	VL	$\leq$15	<30
1-2	L	>15 to $\leq$35	30-35
2-20	MD	>35 to $\leq$65	35-40
>20 {	D	>65 to $\leq$85	>40
	VD	>85	>45

Note: Some N_{10} intervals intentionally overlap to allow for interpretation at transitions. Loose and below from comparison with DCP (AS 1289.6.3.2). Dense and above adapted from [21]. Friction angle is a general guide only.

Table 5: Proposed DPSH correlations for clay

DPSH N_{10}	Consistency	Range (kPa)
<1 {	VS	$\leq$12
	S	<12 to $\leq$25
1-3	F	>25 to $\leq$50
3-6	St	>50 to $\leq$100
6-11	VSt	>100 to $\leq$200
>11	H	>200

Note: Some N_{10} intervals intentionally overlap to allow for interpretation at transitions. Adapted from [23].

It was found in a study into projectile impact in sand [22] that relative density was not correlated with dynamic penetration above 60% (the minimum density in that study), which was inferred to be because the penetrating object compacts the sand in the impact zone. It is possible that a similar effect limits sensitivity at high relative density for the DPSH and other dynamic tools.

5. CONCLUSIONS

Areas of construction material extraction can have complex histories as pits are expanded or separated into smaller areas by the construction of embankments. The progressive back-filling of the pits can have a mixture of local and imported materials. The quality of the backfilled areas for future land uses depends on the methods of filling used and progressive monitoring of the compaction achieved. Tools that measure penetration have the benefit of directly measuring the compaction achieved. It is well known that the commonly used tools can achieve different depths and can also respond differently to differing material types. It is shown here that these differences are likely to be related not just to differing energy inputs but also to fundamental differences in failure mechanisms occurring during penetration.

It is recommended that correlations between different penetration tools should be conducted with care and, in addition to considering differing material types, should also consider the limited range of values over which a correlation can be expected. In particular, the effect of approaching refusal for each tool should be evaluated in the dataset before attempting a correlation. Correlations that are developed without regard to the variations in sensitivities of the tools are likely to be of limited use.

Correlations between DPSH and DCP (cone angle 30°) found that for sand the DPSH had lower N_{10} with similar trends of N_{10} values with depth. This is inferred to indicate that the two tools penetrate the sand with a similar mechanism of soil failure but with differing energy inputs. For a clay embankment, the DPSH was found to have a progressively increasing N_{10} which was higher than the DCP N_{10} values. The DPSH N_{10} values were higher than the DCP values. These relationships were inferred to be the result of differing failure mechanisms in the soil, i.e. compression-dominated failure at the face of the DPSH and shear-dominated failure around the low-angle cone of the DCP.

6. ACKNOWLEDGMENTS

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