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SPATIAL AND TEMPORAL VARIABILITY IN A RESIDUAL SOIL PROFILE

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ABSTRACT

It is well understood that that there is variation inherent in all testing techniques, and that all soil and rock materials also contain some degree of natural variability. Less consideration is normally given to variation associated with natural material heterogeneity within a site, or the relative condition of the material at the time of testing. This paper assesses the impact of spatial and temporal variability upon repeated *insitu* testing of a residual soil and rock profile present within a single residential site over a full calendar year, and thus range of seasonal conditions. From this repeated testing, the magnitude of spatial and temporal variation due to seasonal conditions has demonstrated that, depending on the selected location and moisture content of the subsurface at the time of testing, up to a 35% variation within the test results can be expected. The results have also demonstrated that the completed *insitu* test technique has a similarly large measurement and inherent variability error and, for the investigated site, up to a 60% variation in normalised results was observed. From these results, it is recommended that the frequency and timing of *insitu* tests should be considered when deriving geotechnical design parameters from a limited data set.

Keywords: Inherent soil variability, measurement error, temporal variability, coefficient of variation, Dynamic Cone Penetrometer, Moisture Content,

INTRODUCTION

Residual soil materials are known to be heterogeneous, and all *insitu* and laboratory tests are accepted to contain some aspect of uncertainty (equipment error; operator, spatial or temporal variation) associated with them [1]. In Limit State Design (LSD) allowances are made for this inherent variation and measurement error when determining design parameters or characteristic values from a dataset of soil test results (*insitu* and/or laboratory test results), by the selection of a (generally) conservative value for adoption in design. For example, the recommendation of [2] is in the absence of specific local test data, a characteristic value determined by statistical methods should produce a design parameter such that “a calculated probability of a worse value governing the occurrence of the limit state under consideration is not greater than 5%”.

It is also accepted that the results of material testing can be affected by moisture content [3]. Accordingly, the time of year that an *insitu* test is completed or a material sample obtained will influence test results, as the moisture content of the sub-surface varies based on recent climactic conditions. This is especially true of the near-surface and “active zone,” the region defined as the depth to which seasonal changes in moisture content occur.

As site investigations are often completed within a single period of onsite work, and laboratory testing conducted upon representative samples taken during this limited duration of site visitation, all results are indicative of the material conditions at the single time of material sampling. Accordingly, when material parameters are determined for LSD, although spatial variability across the site and variation in results due to errors within the completed tests can generally be accounted for by suitable geological and analytical models respectively, no allowance for any temporal variability of results is routinely applied.

This paper summarises a field study completed to quantify the variation within the results of an *insitu* testing program repeated upon a single site over a period of 12 months, and the potential influence that the time of site testing may have on typical design parameters. Both the temporal and spatial variability of a simple *insitu* penetration test has been investigated by the repeated testing of a single site over a full cycle of seasons (and thus soil moisture content variation). This paper incorporates data presented by [4] as well as additional data collected to extend the duration of the study.

TEST EQUIPMENT

The *insitu* test repeatedly utilised for this study was the Dynamic Cone Penetrometer (DCP), a simple, portable and low cost tool commonly used as an indicator of strength and variation of the ground profile. An Australian Standard test method [5] was adopted for all tests completed at the test site.

The results, denoted Penetration Resistance (PR), produced by repeated hammer blows (weight drops) during the DCP test are reported as either: (a) the number of blows required to produce a rod penetration of a standard length; or (b) the length of rod penetration produced per single hammer blow.

DCP test results are, via generic correlations, used to infer relative density / consistency categories or to derive material parameters (e.g. shear strength, California Bearing Ratio (CBR) or modulus values).

Differences exist between the Australian [5] standard test equipment and that specified by other countries [6]. Specifically, the hammer weight, drop height and the dimensions of penetration cone may vary. However, as the energy imparted upon the rod is approximately equal, correlations derived by testing completed in any locality are often adopted by others without modification. Existing publications suggest that this assumption may [7], or may not [8] be appropriate.

SITE DETAILS

The site of the repeated testing was a residential site located in Chapel Hill, a suburb of Brisbane, Australia. The subsurface was comprised of a residual soil profile transitioning into weathered phyllite rock by a depth of approximately 1.8m.

Particle Size Distribution (PSD) tests were completed upon the residual soil materials at depths of 0.25m, 0.75m and 1.25m, and a USC classification of Clayey Sand with Gravel was derived based on the resultant grading curves and Atterberg Limits. The completed PSD tests also indicated an 8 to 12% increase in gravel content across the depth profile analysed (i.e. higher gravel content with increased depth). This is typical of a residual profile, as indicatively shown in Fig. 1.

Fines were evaluated to be of medium plasticity, and the site location inferred an “active” zone of approximately 1.5m was expected to exist, as indicated by the applicable Australian Standard [9].

STUDY METHODOLOGY

The completed study involved repeating a standard suite of insitu testing and sampling of the site five (5) times over a full calendar year. The selection of 12 months as the duration of the study was to enable a test variation over a full seasonal cycle to be observed.

Each period of testing involved the determination of site conditions and spatial variation across the site via repeated DCP testing. Three (3) locations (sub-sites) within the Chapel Hill site were defined, offset from each other by 12 to 15 m. At each investigation phase, as identified in Fig. 2, multiple DCP tests were completed at each of the three (3) spatially discrete locations. By the assessment of the difference between the multiple DCPs completed at each sub-site and comparing the resultant averaged DCP profiles between each sub-site, the inherent variability of both the soil and measurement error associated with the test site and test was assessed. Similarly, by comparison of the DCP tests results obtained for each sub-site at each phase of investigation, and thus the change within the material state the period between tests, the temporal variability of the material was assessed.

Insitu moisture contents were determined for the initial 1.2 m profile within each sub-site, and thus the change in moisture content could also be compared to the variation in produced DCP profiles. This allowed the definition of the depth of the “active” zone within the site, and the variation of DCP penetration rate with field moisture content.

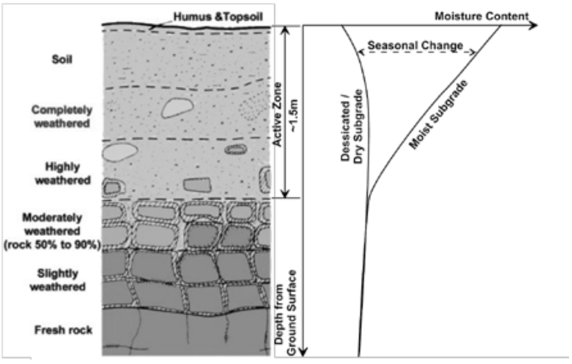

Fig. 1 Inferred weathered profile and expected “active” zone of site (after [9, 10])

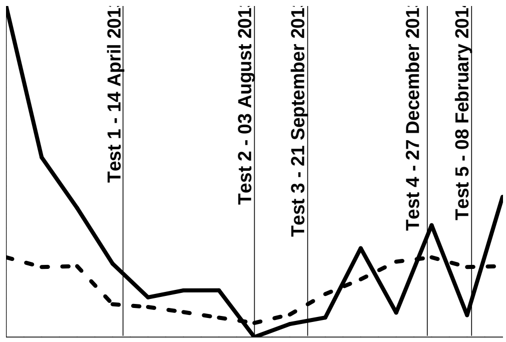

Fig. 2 Observed (solid) and median (dotted) monthly rainfall values and test intervals

RESULTS

For each period of testing, a typical DCP profile was produced for each sub-site by the averaging, by depth, of PR values for all tests completed (n = 1 to

Table 1 Coefficient of Variation (COV) of DCP profiles within identified material units, top 1.5m of subsurface

ID	Test Date	Co-efficient of Variation (COV) of each material unit (%), top 1.5m material profile					
		Site A		Site B		Site C	
		Range	Average	Range	Average	Range	Average
1	14 Apr. 2013	17 – 43	32	0 – 46	27	20 – 47	24
2	03 Aug. 2013	17 – 47	26	18 – 49	33	30 – 71	34
3	21 Sept. 2013	22 – 30	26	12 – 30	23	6 – 17	12
4	27 Dec. 2013	23 – 37	30	23 – 39	29	12 – 31	23
5	08 Feb. 2014	19 – 40	31	28 – 29	29	24 – 37	32

4). As shown in Fig. 3, a PR versus depth profilewas produced, along with an estimate of the deviation from these values. This variation is shown as the maximum and minimum value envelope overlaid upon the averaged PR profile. Based on the average PR value, the encountered subsurface profile was also categorised into depth intervals of similar consistency or relative density.

Inherent Variability and Measurement Error

An assessment of normalised variation displayed within each sub-site's typical DCP profile was made, based on the calculation of a Coefficient of Variation (COV) value both for each individually identified material unit and averaged over all identified material units present within each sub-site. The COV values, as summarised in Table 1, is interpreted to present a combination of both the inherent heterogeneity of the soil material being tested and the measurement error associated with the DCP test methodology. By inspection of Table 1, it can be seen that the average COV encountered for comparative profiles is 27.4% across the full study length, and varies (with the exception of a single value) between 23% and 34%.

Spatial Variation

Spatial variability was assessed based on comparison of the results collected across the site at each of the five (5) testing periods. Average DCP profiles produced at each sub-site were compared by observed PR value at regular (0.1m) depth increments, and combined to construct a single DCP profile representative of the full site for each date of test, as shown in Fig. 4.

After controlling for the variation in results due to testing / inherent error, as described previously, the spatial variability of the site observed at each test period was quantified by the calculation of residual COV values. Spatial variability (i.e. COV values above the variability associated with equipment and natural heterogeneity error) was observed in 59% of the results (44 of 75 records), with basic statistics of the quantified spatial variability for each test phase summarised in Table 2.

Within the normalised spatial variation calculated, values of up to 70% were observed, with a median and average of 4.5% and 9.5% respectively. Via inspection of the data and from formal assessment by linear regression no significant relationship between the spatial variability magnitude and depth was identified.

Accordingly, it is recommended that both inherent variability ($\bar{x}$ = 27.4%) and spatial variation ($\bar{x}$ = 9.5%) values should be assessed, and accounted for, equally across the full length of the DCP profile. This static COV of approximately 37% is similar to the DCP repeatability reported by others [7].

Temporal Variation

Simple comparison between the data available for

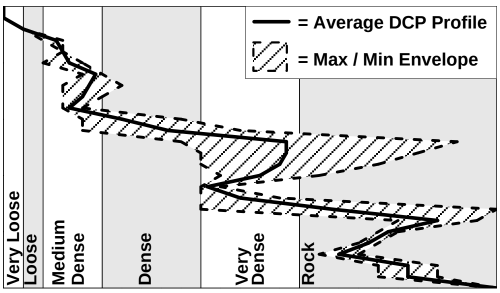

Fig. 3 Typical DCP plot showing averaged profile and range of observed values versus depth.

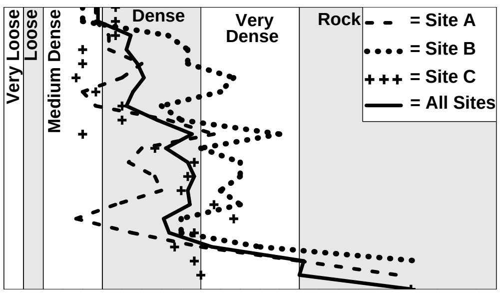

Fig. 4 Plot showing averaged DCP profiles for tests completed in December 2013

Table 2 Summary of spatial variation observed across site, by test period

Test ID	Normalised Spatial Variation (%)		
	Range	Average	Median
1	0.0 – 69.9	21.1	19.5
2	0.0 – 23.7	6.1	0.0
3	0.0 – 25.1	8.0	7.7
4	0.0 – 23.3	6.4	0.0
5	0.0 – 19.0	5.8	0.0
ALL	0.0 – 69.9	9.5	4.5

each sub-site produced a range and magnitude of variation observed across the full year of site testing, and produced a value of temporal variation for each 0.1m depth interval. The profile of temporal variation produced for each sub-site are shown in Fig. 5, and inspection of these profiles indicate the largest temporal variation is associated at the existing ground surface. The magnitude of temporal variation decays from above 45% at the ground surface to 0% at a depth of 1.0m. Below this depth the temporal variation appears to stabilise about an average value, with sub-site 'A' indicating a higher temporal variation at depths below 1.0m ($\bar{x}$ = 26%) than the other two (2) sub-sites ($\bar{x}$ = 3 – 11%).

Linear regression analyses indicate the strongest relationship, assessed by correlation co-efficient (R^2) values, consistently exists when the data is isolated from the ground surface to depths of 0.8m to 1.0m. This suggests that data below such depths does not display the same depth related relationship, and indicates the "active" zone of the investigated site is limited to a depth of approximately 1.0 m.

The observed general decrease in temporal variation over a specific depth interval extending from the ground surface is interpreted to be due to the variation in the moisture content present within this depth interval over the duration of the study. As moisture content influences DCP results, and the largest moisture content variation would be expected to occur at the surface level and decrease with depth

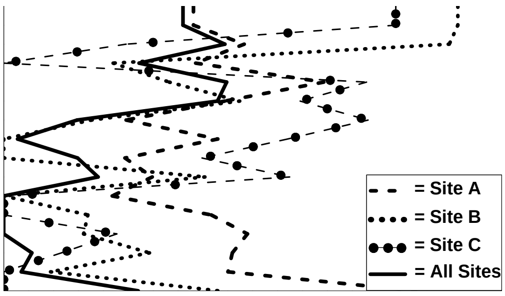

Fig. 5 Temporal variation within comparable DCP profiles over study duration

(refer Fig. 1), the temporal variation observed would also be expected to decrease with depth.

Total Observed Variation

Combining the three (3) isolated sources of variation, an estimate of total variation profiled against the initial 1.5m subsurface interval has been produced (Fig. 6). This indicates the magnitude of total variation varies from up to approximately 60% within the top 0.50m ($\bar{x}$ = 54%), before decaying to oscillate about a lower bound value below depths of 1.0m ($\bar{x}$ = 41%).

These derived values also fall within the range of variation associated with another commonly employed test, the Standard Penetration Test (SPT), as detailed by [1]. This previous study found the range of total variation of SPT testing in sand materials was 19 to 62% ($\bar{x}$ = 54%).

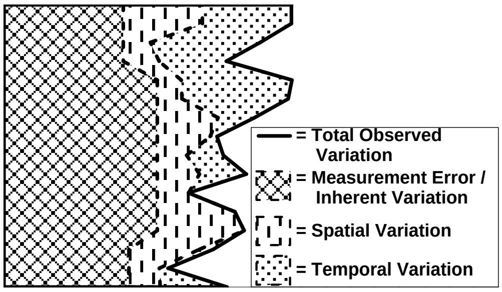

Fig. 6 Total observed variation with DCP results, categorised by source of variation and error

CORRELATION WITH SOIL MOISTURE CONTENT AND RAINFALL

Disturbed samples were obtained and the *inistu* moisture content determined (n = 49) for a depth range of between 0.25m to 1.65m. The completed testing allowed the construction of a soil moisture content profile for each averaged DCP profile. The average and range profiles produced for the combined (full site) dataset is shown in Fig. 7, with the results calculated for the individual sub-sites summarised in Table 3.

Although the average field moisture content was observed to vary across the site, the largest range of variation over the 12 month study were consistently identified to exist at the surface, and then decrease with depth. It is also noted that within sub-site A, the moisture content increased with depth, which has been interpreted to be due to the temporal groundwater level located at 1.45m depth. However, at all sub-sites the minimum range in results was observed to exist at the 1.0m depth, again suggesting the "active" zone is located above this level. On average, the magnitude of moisture content variation

Table 3 Standardised range, average and COV of *insitu* moisture content, top 1.0m of subsurface

Depth (m)	Moisture Content (%)								
	Site A			Site B			Site C		
	Range	Mean	COV	Range	Mean	COV	Range	Mean	COV
0.25	8.7 – 23.3	14.7	41	8.8 – 20.6	15.3	33	16.5 – 21.0	18.1	9
0.50	11.3 – 19.4	14.5	23	11.0 – 17.6	14.7	17	9.5 – 16.9	12.6	22
0.75	11.3 – 19.9	15.4	20	8.4 – 14.6	12.8	20	5.7 – 12.9	9.6	33
1.00	17.3 – 23.4	20.1	12	10.8 – 12.3	11.5	5	6.5 – 10.9	8.8	23

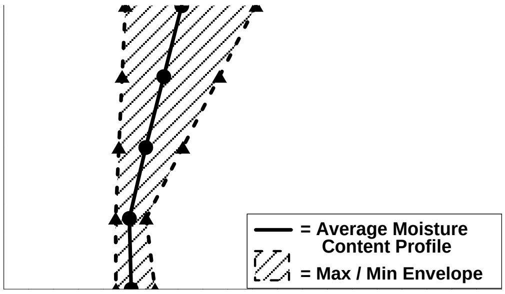

Fig. 7 Moisture content and range of variation observed over 12 month study duration

at 1.0m depth was 40% that observed at the sample taken closest to the surface (0.25m).

Correlation between the soil moisture content variation and the change in the PR results between consecutive test periods was completed to in order to demonstrate the relationship between the two (2) measured parameters. A statistically significant (n = 45, p = .00) linear relationship was determined for the difference in all results, as detailed in Eq. 1.

$$\text{PRV (blows/100mm)} = -0.39 \times \text{MCV (\%)} \quad (1)$$

Where, for the interval between repeated tests:
PRV = PR change (blows / 100mm penetration)
MCV = Moisture content change (%)

By isolation of the PR and moisture content values observed at each 0.25m depth increment, variations of the PVR:MCV linear multiplier and the strength of the relationship (R^2) were observed, as summarised in Table 4. The strongest (R^2 = 0.5) relationship between moisture content and PR values occurred nearest to the surface (0.25m depth) and this relationship generally decreased with depth.

Table 4 Correlations between the observed moisture content variation and PR variation recorded during consecutive testing periods

Depth (m)	Sample size (n)	Relationship between PR and MC variation	R^2
0.25	12	PRV = -0.30 MCV	0.50
0.50	12	PRV = -0.56 MCV	0.24
0.75	12	PRV = -0.31 MCV	0.11
1.00	9	PRV = -0.49 MCV	0.43
ALL	45	PRV = -0.39 MCV	0.25

Combining Eq. 1 and the annual range of moisture content variation experienced over the 2013 / 14 testing period (refer Fig. 7), the expected influence that moisture content has upon the DCP PR rate, and thus the variation of PR values based on the time of testing, has been estimated. This analyses indicated that the moisture content variation within the subsurface materials would be expected to produce an annual variation in DCP PR values of 4 hammer blows at the ground surface, and 1 to 2 hammer blows at the base of the "active" zone.

Comparing the calculated annual variation in PR values due to moisture content variation and calculating this range as a percentage of the "average" DCP PR profile calculated for the site, the equivalent percentage variation in PR result was also obtained. This indicated that the moisture content variation would result in ±25% variation about the mean PR value for depths of up to 0.5m, and ±10% variation in PR values over the remainder of the "active" zone. Such values approximately replicate the temporal variation magnitudes (refer Fig. 5).

As shown in Fig. 8, the total rainfall in the 3 month period preceding each suite of DCP testing [11] was compared to the proportion of averaged PR that indicated "dense" or above (PR $\geq$ 5) materials. A distinct increase in the proportion of the subsurface that reported such values occurs as the rainfall magnitude decreases and the subsurface is allowed to dry. Similarly, the profile showing the percentage of the top 1.5m subsurface profile interpreted to be "medium dense" or below (PR < 5) largely reflects the shape of the profile of the total rainfall of the preceding three (3) months.

IMPLICATIONS FOR DESIGN

CBR values are commonly derived from the results of DCP testing, and CBR values are then commonly incorporated into design as the basis for the estimate of a deformation parameter. Thus, the variation defined for the DCP PR values would also influence any correlated CBR values.

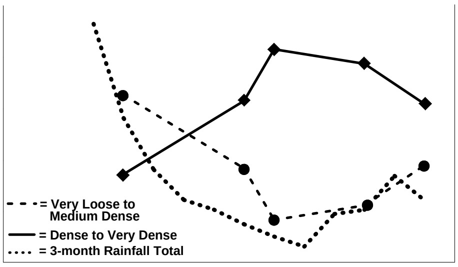

Fig. 8 Proportions of subsurface classified to intervals of relative densities compared to 3 month preceding rainfall total

By adoption of a generic DCP and CBR value correlation [12], the resultant range of CBR values produced by the derived variation associated with averaged PR values was calculated. The CBR range calculated for such values are summarised in Table 4, and indicate that for the one year that the site was monitored, *insitu* testing would have yielded resultant CBR values that would have displayed a variation of between ±46% (at ground surface) and ±28% (at 1.0m depth) about the average CBR value.

Table 4 *Insitu* CBR variation based on depth from surface and total observed PR variation

Depth (m)	PR Value (All sub-sites, all tests)		*Insitu* CBR (%)	
	Mean	Total Var. (%)	Min.	Max.
0.00	3.2	58	2.1	5.9
0.25	4.2	52	3.4	8.0
0.50	5.5	55	4.4	11.0
0.75	6.2	44	6.5	12.6
1.00	7.4	39	8.7	15.5

SUMMARY AND CONCLUSION

A residential site in suburban Brisbane was monitored by repeated DCP testing over a twelve month period. The magnitude of various sources of test error and result variation associated with the DCP test has been derived from analysis of the recorded PR values (blows / 100mm rod penetration).

Inherent material variability and measurement error was calculated to average 27.4% and site-specific spatial variation was derived to average 9.5%. Thus, for any DCP completed at the site, a constant average variation magnitude of 36.9% was demonstrated to exist for any individual PR value.

The "active" zone was found to be approximately 1.0m deep at the site. An average temporal variation of 22% was observed to occur between the ground surface and a depth of 0.5m. Variation of PR values totaled 58% at the surface before decreasing to approximately the static variation value (36.9%) at depths below of 1.0m.

Generic correlation between PR and *insitu* CBR values indicated the constant (36.9%) PR variation would result in a range of ±26% about the CBR calculated from the mean PR value. Incorporating the maximum temporal variation (22%) would increase the resultant CBR range to ±46%.

Accordingly, the results of DCP values should not be relied on for high accuracy, and the results of a DCP test should be viewed as representative of the site under the conditions at the time of testing only. Consideration for the season of testing and likely moisture content of the "active" zone of soil within annual variation should be considered when deriving characteristic parameters for geotechnical design.

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