Case studies for temporal variability In site characterisation

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ABSTRACT

While site investigation data is typically focused on the spatial variability for site characterisation, those properties may change with time. Temporal variability needs to be considered in the design and construction of roads and high-level foundations. Seasonal variation occurs in the active zone and long-term changes occur 2 to 5 years after construction using expansive clay materials in adverse climate conditions. The latter may occur below the zone of seasonal variation.

A case study for seasonal changes in subgrade strength at an uncovered test site when tested at 5 different times of the year. Measurement accounted for 30% of the variation, while temporal and spatial variation accounted for an additional 30% variation over the 1-year period of testing. An appropriate probability distribution function (PDF) is required for characteristic values.

Constructing embankments to the equilibrium moisture content (EMC) is more important than the optimum moisture content (OMC), which is a short-term construction expedient. Time Domain Reflectometry (TDR) probes were used to monitor embankment moisture changes over a 4-year period for a new road construction on expansive clays. This included 1) an existing 30-year-old embankment during the project planning phase, 2) a trial embankment during design, and 3) the new constructed roadway embankments. All demonstrated the importance of understanding the EMC when expansive clays are being used for embankment construction. Results in other climatic environments are compared. The results show subgrade CBR tested at OMC is meaningless for such soils and in those extreme climates.

Keywords: Equilibrium moisture content; subgrade; coefficient of variation; temporal variability; PDF

1. Introduction

The ambient weather conditions can have a significant effect on near-surface strength tests for shallow foundations and subgrades. Even with standard testing, variability can occur due to:

1. Spatial and material variability
2. Testing variability
3. Time of testing

Characterisation of material testing variability is provided by Phoon and Kulhawy (1999). Field and laboratory inherent testing variability are also provided.

Shallow foundations, pavements and subgrades are sensitive to seasonal and daily changes in strength and stiffness. Yet an SI is usually conducted once and not at the most adverse time of year. Though useful data, it is uncommon to record the time of year and rainfall in the preceding weeks of an SI. The relevance of the time of year to test results is summarised in Look (2022) and detailed further in this paper.

The results of soil material testing can be affected by moisture content. The moisture content of the sub-surface varies based on recent daily or seasonal changes and any insitu or material sample obtained will vary accordingly in the near-surface active zone. A stable zone at depth is unlikely to be affected by such seasonal variation.

Site investigations and laboratory testing conducted upon representative samples are indicative of the material conditions at the time of sampling. Allowance for temporal variability of results should be considered.

Some countries use a 4-day soak CBR while some States in Australia use a 7- and 10-day variant as 4 days does not represent an extreme flood event in Australia.

Geotechnical investigation data collected on a given day may not envelope an adverse condition. Temporal moisture variation occurs as:

1. Seasonal variation in the active zone. This is an annual change, which affects both strength and movement in the upper ground profile. Case study 1 is used to illustrate these changes. This field study was carried out to quantify both the temporal and spatial variability of a simple insitu penetration test. The repeated testing of a single site occurred over a full yearly cycle.
2. Long term changes which occur 1 to 5 years after construction in expansive clay sites and in adverse climate conditions. Case study 2 presents the results of long-term monitoring to show how and when these changes occur. Long term deterioration of cut slopes also occurs and is not discussed herein.

Although not the main focus of this paper, the data in case study 1 is used to show how inappropriate statistics used in the analysis of geotechnical data may be misleading.

1.1. Seasonal moisture content changes

Below the active zone seasonal changes are unlikely, although ground water variations may occur. The active zone is subject to seasonal variation with resulting moisture content and strength changes.

Pavement design is affected by the subgrade CBR value used, but this value does change over the seasons and in the long term. The moisture content produces volume change in expansive clays and affects the strength for shallow foundation designs.

The depth of active zone is dependent on the Thornthwaite moisture index (TMI) – a climatic factor that considers both rainfall and evaporation. Based on the TMI the active zone may vary from 1.5m in temperate and wet climates to 4.0m in arid climates (AS2870, 2011). A case study is used where the active zone is approximately 2.0m based on the TMI. However, at this test site the residual soil profile transitions to an extremely weathered rock by 1.8m depth.

1.2. Long term moisture content changes

Long term moisture content changes occur below the zone of seasonal variation. Designing and constructing embankments close to the optimum moisture content (OMC) is a standard construction practice, which is targeted for construction. This does not necessarily represent the long-term condition, as the soil will change in moisture over time and with consequential movement and strength changes if an expansive clay. For granular material (low fines) the changes are of low consequence.

Constructing embankments to the equilibrium moisture content (EMC) is more important than the OMC, which is a short-term construction expedient (Look, 1996 and 2005). The EMC is equivalent to the OMC for climates with 500mm to 1,000mm annual rainfall. Thus, countries or States within that rainfall range would use the OMC criteria without adverse effects. In dry (< 500mm) and wet (> 1,000mm) climates, significant moisture changes occur which produce movements and loss of strength for expansive clays.

Thus, the subgrade CBR tested at OMC is meaningless for such soils and in those extreme climates. Time Domain Reflectometry (TDR) probes were used to monitor embankment moisture changes over a 4-year period for a new road construction on expansive clays. This included 1) an existing 30-year-old embankment during the project planning phase, 2) a trial embankment during design, and 3) the new constructed roadway embankments. All demonstrated the importance of understanding the EMC when expansive clays are being used for embankment construction. Results in other climatic environments are compared.

1.3. Probability distribution function (PDF)

The analysis for case 1 uses the probability distribution function (PDF) to illustrate the variability. The PDF is the relative likelihood a random variable will assume a particular value. The area under a PDF is unity. The most known distribution function is the Normal Distribution (the bell curve). This uses a mean and standard deviation as its arguments. The mean describes the value around which the bell curve is centred. The mean, mode and median are equivalent. The standard deviation describes the spread of the results. The coefficient of variation (COV) is the ratio of the standard deviation and mean value.

There are over 35 distribution functions with the “best fit” distribution function assessed through goodness-of-fit test to the data. Using such statistical tests, the normal PDF test is poorly ranked for most geotechnical data (Look, 2015), while the log normal provides good fit although not necessarily the best ranked PDF. The analysis which follows shows both the normal and log normal PDF with be input data.

2. Case 1 – Seasonal variation

2.1. Background – Case study 1

The site of the repeated testing was a residential site located in Brisbane, Australia. This was my back yard - hence unlimited access to carry out repeated tests over one year for research students. This is a sub-tropical climate and high summer rainfall between December to November (Figure 1). The 5 No. test periods are shown.

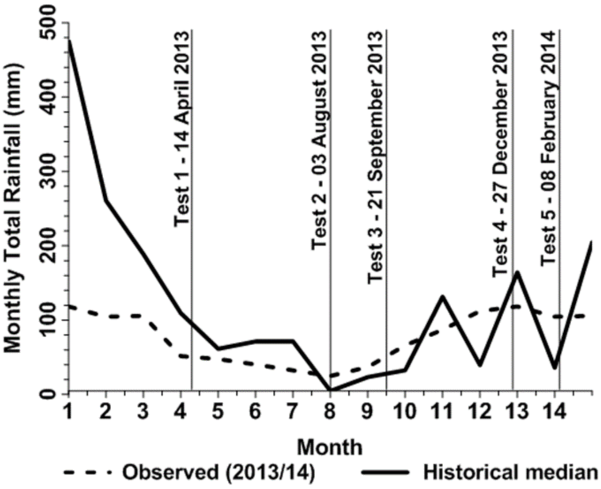

Figure 1. Observed (solid) and median (dotted) monthly rainfall values and test intervals

The subsurface comprised a residual soil profile transitioning into weathered phyllite rock by a depth of approximately 1.8m. Testing details and further background is provided in Mellish et al. (2014).

The Dynamic Cone Penetrometer (DCP) was used as an indicator of strength and variation of the ground profile. Three (3) locations within the site were defined, offset from each other by 12 to 15 m.

Intact CBR samples were obtained using 150 mm sample tubes driven into the ground. These were extruded from the tube, wrapped, and taken to the laboratory for testing. Those samples were progressively dried back and moisture contents of the top 20 mm taken with the corresponding CBR value.

At each investigation phase identified in Fig. 1, multiple DCP tests were completed at each of the three (3) spatially discrete BH locations. The difference between the multiple DCPs adjacent to each BH compared the averaged DCP profiles between each test location, the inherent variability of the soil, measurement error associated with the DCP test, and spatial variability across the test site was assessed. Similarly, comparison of the DCP tests results obtained for each location at each phase, established the change within the material state, for the temporal variability to be assessed.

2.2. Summary of test results

Figure 2 (Mellish et al., 2014) shows the DCP profile coefficient of variation (COV) due to:

1. Measurement – repeated tests at the same location
2. Spatial – three tests in a triangle 12 m to 15 m apart in a uniform site and tests to 2m depth
3. Temporal – 5 tests repeated over a 12-month period in the same 3 locations

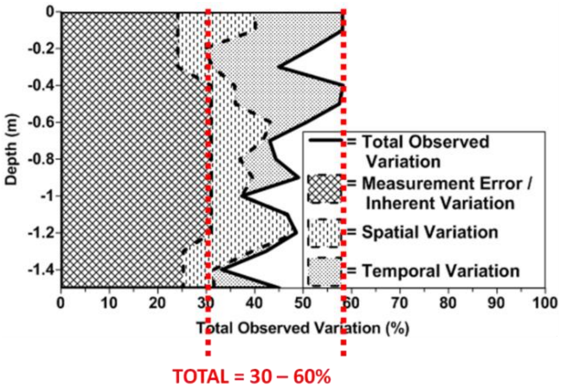

Figure 2. Measured variation with DCP results, categorised by source of variation and error

The testing demonstrated that measurement errors and inherent variations had a testing variance of up to 30% (Figure 2). When combined with spatial and temporal considerations the variance increases to 60%.

2.3. Temporal variation

Table 1 provides the key temporal statistics used in deriving Figure 2. Table 2 provides other statistics of the DCP profile for the top 2.0m of subsurface at 5 dates and combined (all data).

Table 1. DCP profile for top 2.0m of subsurface at 5 dates and combined (all data) with key statistics

Date	DCP blows / 100mm			
	10%	25%	Mean	S.D.
All data	2.8	4.5	8.2	5.4
Apr 2013	1.4	2.8	7.7	6.4
Aug 2013	2.3	3.9	7.9	5.6
Sep 2013	4.3	5.5	8.8	4.9
Dec 2013	4.0	5.1	8.5	4.9
Feb 2014	3.4	4.5	8.2	5.3

The COV values, 10% and 25% fractiles are summarised, to present a combination of both the inherent heterogeneity of the soil material being tested, the measurement and temporal error associated with the DCP test. Values above 20 are not always reported as this is considered “refusal” for this test.

Table 2. Statistical variability with testing date

Date	DCP blows / 100mm			
	COV	No. of tests	Normal PDF (-) ve values	% Values >20 blows
All data	65.9%	624	6.3%	15.7%
Apr 2013	83.1%	98	11.4%	2.0%
Aug 2013	70.9%	116	8.0%	17.1%
Sep 2013	55.7%	103	3.5%	14.2%
Dec 2013	57.6%	148	4.1%	17.8%
Feb 2014	64.8%	159	6.0%	20.5%

Figure 3 shows the PDF and input for all data, and compares the lognormal, and normal PDF. Using the normal PDF would result in a prediction of 6.3% of values being negative despite a measured value below zero not being possible.

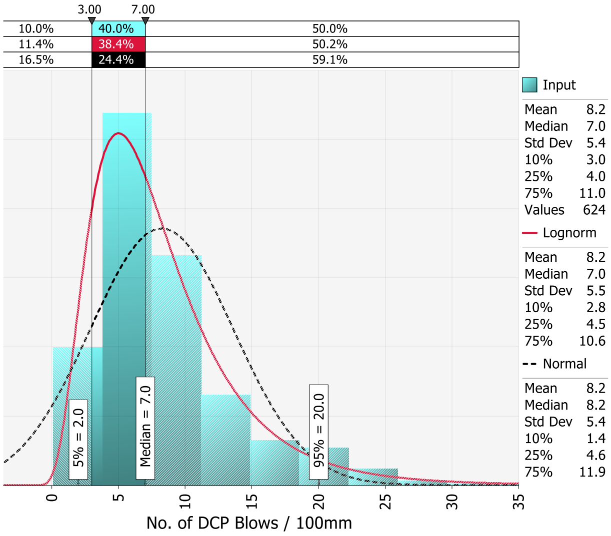

Figure 3. Fit comparison for all DCP data

April and September 213 represent periods at the end of wet and dry rainfall, respectively (Figure 1). The COV is higher at the end of wet weather and lower at end of the dry season. At the 25% fractile, the dry strength is twice that as compared to the wet period. These results illustrate how the time of year of testing at the near surface (top 2.0m) influences the test results. Figures 4 and 5 show the PDFs for April 2013 and September 2013 with 11.4% and 3.5% negative values for the normal PDF. The 5%, 10%, and 25% characteristic values differ by a factor of 4.0, 3.1, and 2.0, respectively.

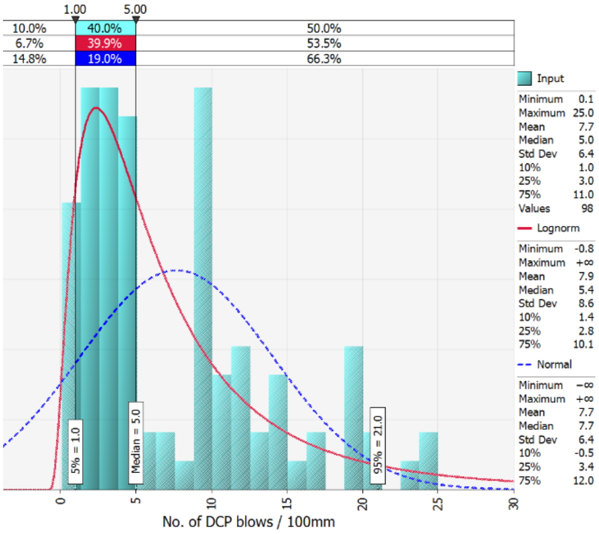

Figure 4. Fit comparison for April 2013 DCP data

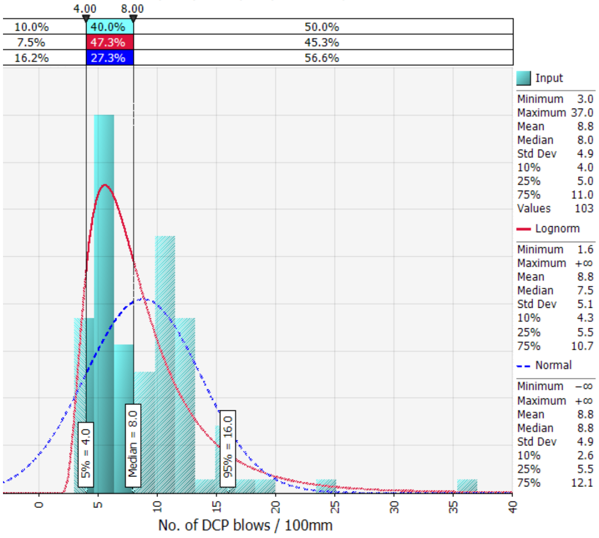

Figure 5. Fit comparison for September 2013 DCP data

Figure 6 compares all the lognormal PDFs into one graph to show how time of year influences the results. In April and September 2013, the median DCP shown would vary from 5.5 to 7.5. At characteristic values less than the median the values the difference is more significant. At the 10% characteristic value, the DCP value changes from 1.4 in April (end of wet period) to 5.5 in September (dry period). This represents a factor of almost 4 over a 1-year seasonal cycle.

2.4. Depth Variation

Table 3 provides a summary of the testing variability with depth. As expected, the variability decreases with depth. The strength also increases with depth. The active zone at this site extends to between 1.8m and 2.0m. The active zone has a COV of ~ 60% near surface and decreasing to < 40% in the stable zone.

Figures 7 and 8 compare the PDFs at 0.5m and 1.8m depth for all dates. These 0.5m and 1.8m depths show and 4.1% and 0.6% negative values for the normal PDF. The COV is 58.9% and 40.1%, respectively.

Comparing the COV suggests that temporal variation is more significant than the depth variation at this site.

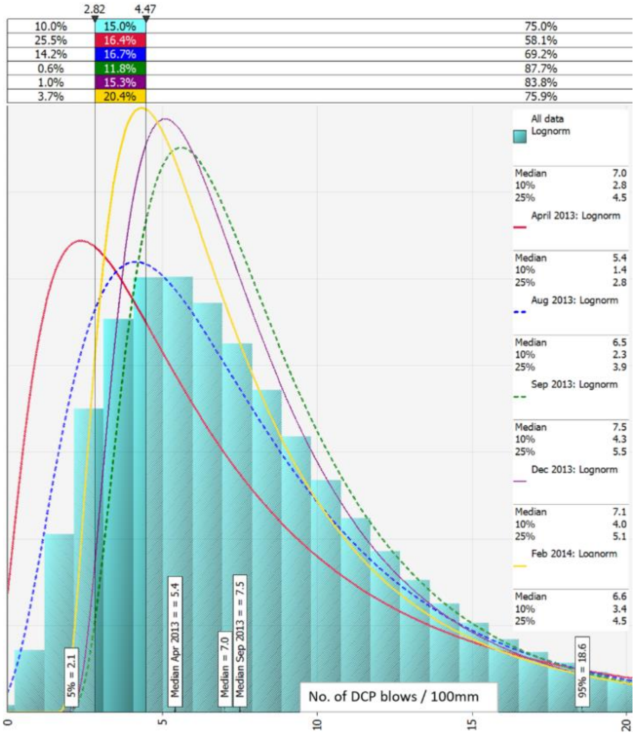

Figure 6. Comparison for all DCP data and different test dates

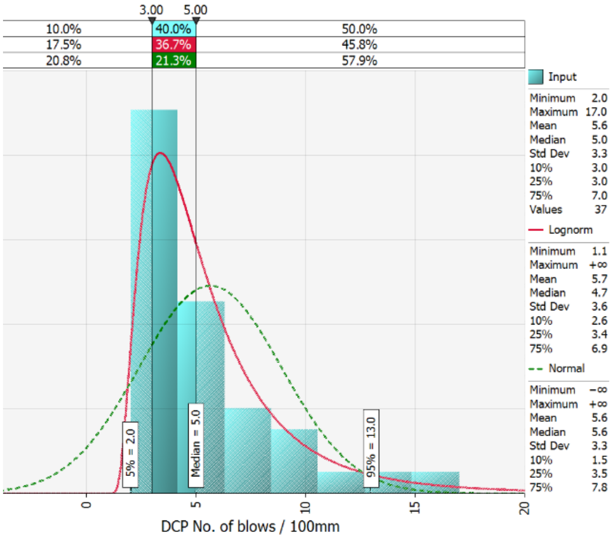

Figure 7. Fit comparison for all DCP data at 0.5m depth

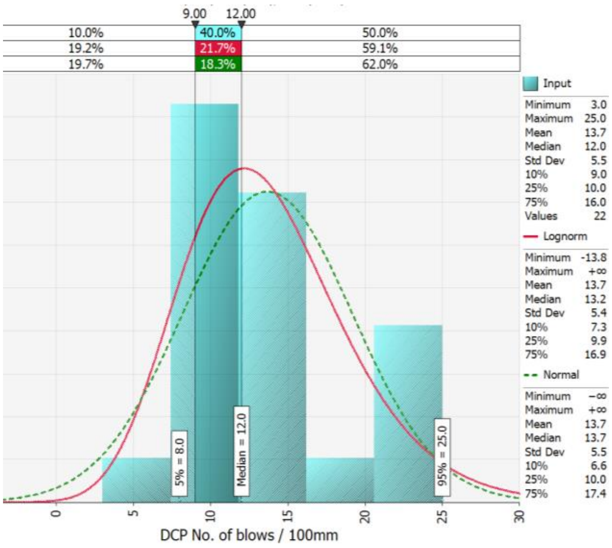

Figure 8. Fit comparison for all DCP data at 1.8m depth

Table 3. Statistical variability with depth for all dates

Depth	**DCP blows / 100mm**			
	COV	**No. of tests**	**Normal PDF (-) ve values**	**% Values >20 blows**
All data	65.9%	624	6.3%	15.7%
0.2m	53.7%	37	3.4%	0.0%
0.5m	58.9%	37	4.1%	0.0%
1.0m	46.9%	35	1.7%	5.4%
1.5m	51.7%	30	2.6%	18.9%
1.8m	40.1%	22	0.6%	40.5%
2.0m	20.0%	8	0.0%	78.4%

2.5. Testing Variation

Each of the 3 BH locations had multiple DCP tests. The results of the 4 DCPs at BH 3 on February 2014 are shown in the PDF of Figure 9. At the 10% characteristic value, the DCP value changes by a factor of 2 if the log normal or normal PDF is used. Above the 25% fractile the log normal and normal PDF are comparable.

The PDF has a COV of 60.3%, and with 4.7% of normal PDFs showing negative values. This is due to testing and material variation given all the tests are at one location and a given date. The aggregation of the DCP results were shown in Figure 2 to show the relative effects of equipment, spatial and temporal variability.

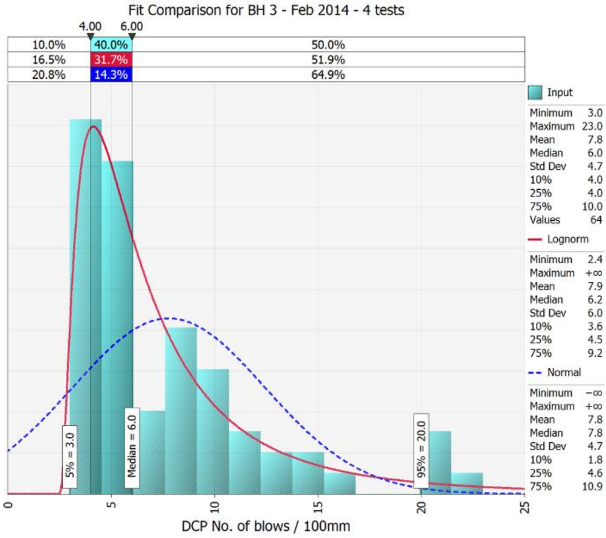

Figure 9. Fit comparison for all DCP data at 0.5m depth

2.6. Relation between COV and errors of the normal PDF

Although, the focus of this paper was to illustrate the effects of temporal variation, another key finding is when not to use the normal PDF for prediction analysis.

Look (2015) showed how assuming a normal distribution PDF produces dubious results for the 10% fractile. Case studies on CBR, pile set, and point load testing were used. The normal distribution was comparable with the lognormal and best fit PDF at the 20% to 30% fractile. At low COVs then the normal PDF applies. This case study further supplements that finding.

Using the DCP tests with the COV and the % of negative values using the normal PDF (Table 2 and 3), the relationship was established in Figure 10. This shows that for this DCP data a normal PDF would not have prediction errors at or below a COV = 30%. As the COV increases from 50% to 60% and 80% the % of negative (and invalid) predicted values are 2.3%, 4.7% and 10.5%, respectively.

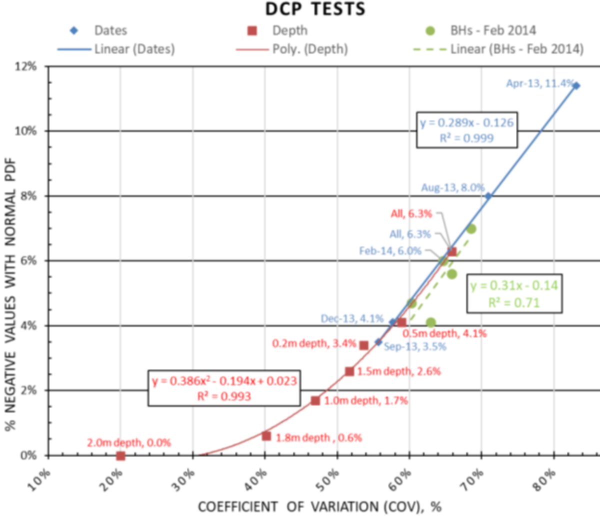

Figure 10. COV compared with the negative values of the normal PDF

Other low values may also not be valid, although statistically permissible. Consideration of removal of outliers should be considered. Figure 5 shows a high DCP value of 37 at 0.9m depth, which is an outlier associated with hitting a stone size, rather than representing the strength of the soil. Such values should be removed from the analysis, although not done in this paper.

DCPs are often correlated to in situ CBR with its own associated conversion uncertainties. Look (2022) states that site contractual issues often arise when CBR tests have a COV greater than 80% and a "uniform" site requires a CBR COV less than 60%.

2.7. Soil moisture content and rainfall

Disturbed samples were obtained and the insitu 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. 11 (Mellish et al., 2014).

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 near surface, and then decrease with depth. The minimum range in results was observed to exist at the 1.0m depth, again suggesting the "active" moisture zone is located at or above this level. This could equally be the cracked zone within the active zone.

Based on the DCP profile the active zone extends to between 1.8m to 2.2m depth, but this could also be due to material change to weathered rock.

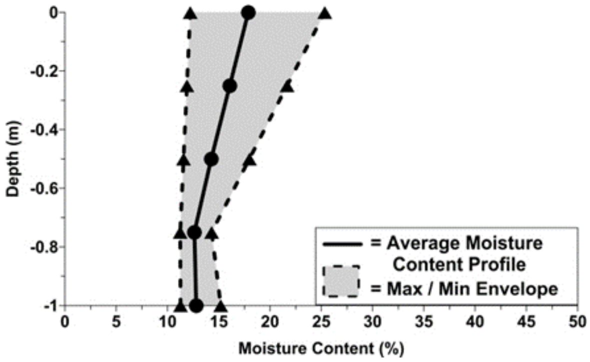

Figure 11. Moisture content and range of variation observed over 12-month study duration

2.8. Temporal variation of CBR

Intact CBR samples were obtained in the upper ground profile and tested in the laboratory. Cut and reduced size samples were also progressively dried back and tested at various moisture contents. This assumes no corresponding change in density on site.

Figure 12 shows that based on the seasonal changing moisture content at this site, the CBR will vary considerably. A CBR of 2.5% at the end of the wet period applies, while a CBR of 5% would apply at the end of dry period. This seasonal variation is a factor of 2.

Based on in situ DCP values (Table 1) and typical CBR corelations, the CBR field value would be 3% and 6% for the wet and dry periods, respectively. Again, a factor of 2 applies between seasons.

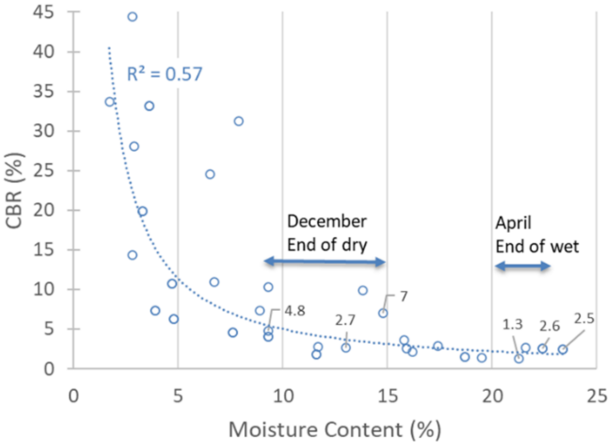

Figure 12. MC @ 0.5 m depth and corresponding CBR. Wettest and driest period lags rainfall

3. Case 2 - Long term variation

The earthworks for the 1990 proposed Cooroy Bypass deviation, Australia, involved cut and fill operations in expansive clays. Moisture studies (Figure 13) were undertaken using time domain reflectometry (TDR) instrumentation (Look and Reeves, 1992a) and detailed monitoring results described in Look (1996, 2015, 2022).

The TDR probes were installed in late 1990, in two trenches designated T1 and T2 (~ 7 km apart), within existing embankments of the same material, to monitor long-term seasonal moisture fluctuations (Look and Reeves, 1992b). These probes measure volumetric moisture content (VMC) and conversions to gravimetric moisture content (GMC) are made with the dry density.

Figure 13. TDR probes installed at existing embankment - Trench T1 Cooroy Bypass 1990

A 1.5 m active zone was assumed at the time of installation of the TDR probes. The figures show that the active moisture zone, which is affected by seasonal variations, extends to below a depth of 1.8 m (Figures 14 and 15). Reactive clays placed within this zone undergo moisture changes due to seasonal moisture variations.

Using the Standard Optimum Moisture Content (SOMC) obtained initially and converting from the volumetric moisture measurements to the gravimetric moisture content, the monitoring showed that the in-service moisture condition is 1.2 to 1.3 times the SOMC in the stable zone.

These 2 trenches were over 7km apart, but constructed of similar clays at the OMC, with measurements showing a similarity in their response to moisture changes. Reactive clays placed drier than this condition would be expected to wet up and expand over time. Design should therefore allow for potential volume changes and the accompanying reduction in strength.

The peak volumetric moisture content was about 42% to 43% in both the active and stable zones. Here, the peak moisture content corresponded to the peak of a 50-day moving average of the rainfall preceding the day of monitoring. While the peak of the wetting phase corresponded to the 50-day moving average rainfall, the base of the drying phase corresponded to the 300-day moving average rainfall pattern.

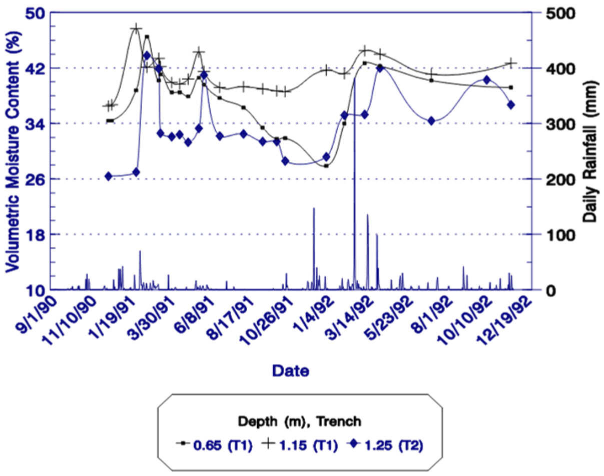

Figure 14. Moisture variations in the active zone (Look,1996)

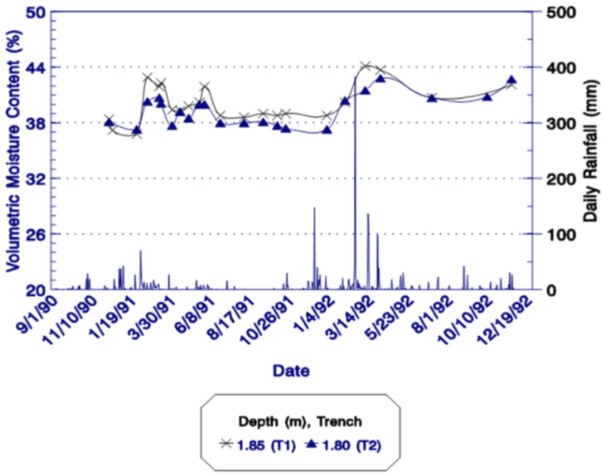

Figure 15. Moisture variations in the stable zone (Look,1996)

3.1. Trial embankment

These moisture studies indicated that the EMC was well above the SOMC, and the densities were lower than the MDD. A trial embankment was constructed in three sections, each with a different initial moisture condition but with the same target density. The moisture contents targeted were 1.0 OMC, 1.2 OMC and as wet as possible (1.2+ OMC). Again, TDR probes were used for long-term monitoring of the VMC.

The results of the trial are presented in Look and Reeves (1992b) and show that irrespective of the moisture content of the various sections of the trial embankment, they all converged to an approximately similar VMC at 9 months (Figure 16) with a more significant variation in the active OWP. In this trial the EMC was in the range of 35% to 38% VMC. This stable moisture content range compares with the 37% to 43% VMC measured in T1 and T2 described previously. When conversion to the GMC is made, the moisture ratio is again 110% to 130% of SOMC.

3.2. Construction monitoring

During construction TDR probes were installed to control the curing period. This instrumentation provided data to assess when sufficient time had passed for moisture equilibration before placement of the critical overlying pavement layers. This minimises damage from movements associated with moisture equilibration. Horizontal profile gauges (HPG) were also installed to evaluate the corresponding movements.

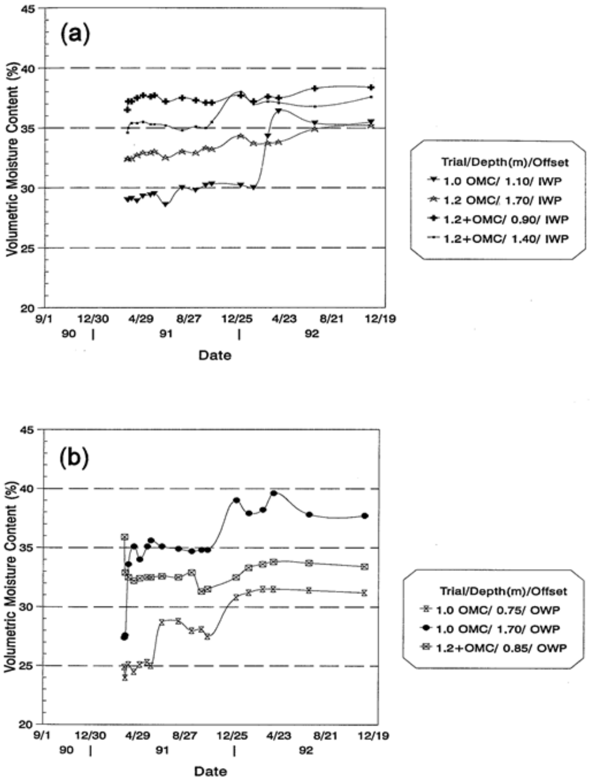

Figure 16. Moisture variations in (a) the stable inner wheel path (IWP) and (b) the active outer wheel path (OWP) of the trial embankment (Look, 1996)

Figure 17 shows the results of monitoring at various chainages during construction, when 120% OMC was targeted, which was the upper limit of practical moisture placement but still under the EMC. Again, this monitoring confirmed the design should target the equilibrium condition. In this case the equilibration occurred in a shorter time than for the trial embankment due to the procedure adopted and a higher rainfall at the time of construction.

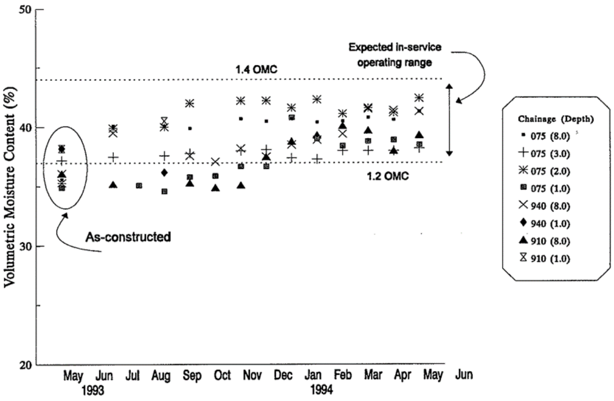

Figure 17. Moisture monitoring during construction for several chainage locations (Look, 1996)

The important lesson from this case study was the requirement to construct as close as possible to the EMC range within the stable zone. One must distinguish between the following two movements (Figure 18):

1. The change to the EMC – a one-off occurrence, and
2. The seasonal movement in the active zone that can be expected very year

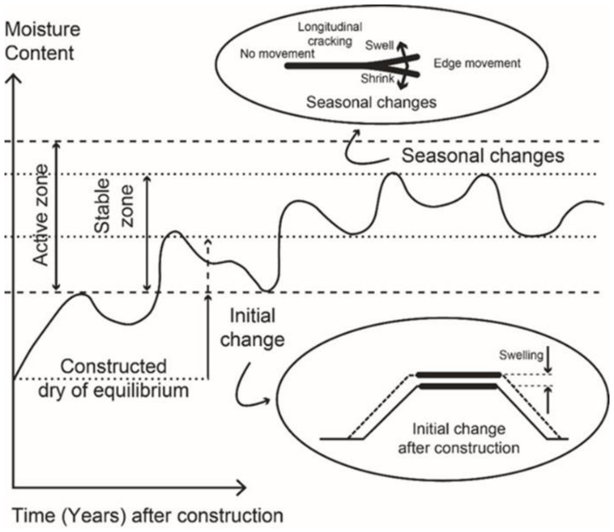

Figure 18. Seasonal and initial movements after construction

Additional data from other monitoring sites show similar trends, and are combined in Figure 19. The weighted plasticity index was found to be a better screening index in residual soils as compared to the plasticity index or liquid limit (Look, 1996, 2016). This analysis shows:

1. For WPI < 1200, the equilibrium moisture ratio is dry of OMC and not correlated to climate.
2. For WPI = 1200 to 3200, the equilibrium moisture ratio shows some dependency on climate.
3. For WPI > 3200, the equilibrium moisture ratio is sensitive to climate.

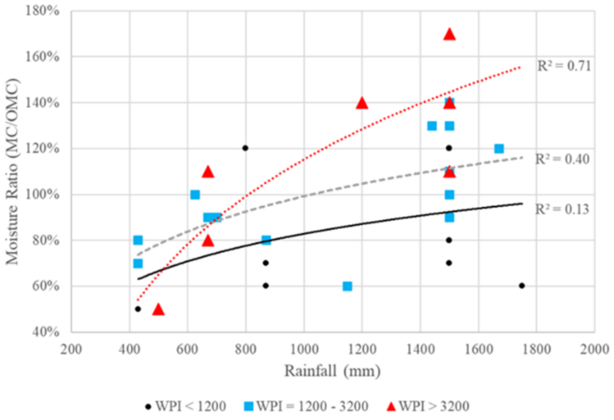

Figure 19. Equilibrium moisture content for varying rainfall and WPI (Look, 1996)

Therefore, if expansive clay material does not have the EMC as a design consideration, significant changes in moisture (and hence movement) can be expected. The data varies from dry of OMC for rainfall less than 500 mm, to wet of OMC for rainfall greater than 1,000 mm.

4. Conclusion

Climate affects design considerations. Using data obtained over 1 year of monitoring shows the DCP and CBR results obtained at the dry period can be twice the value obtained at the end of a wet period.

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, an average variation magnitude of 36.9% was measured. An average temporal variation of 22% was observed to occur between the ground surface and a depth of 0.5m.

A coefficient of variation of 80% for DCPs can be expected to have over a 10% negative (incorrect) values if a normal PDF is adopted A Lognormal PDF is recommended for statistical analysis of such results. Below a COV of 30%, this effect is not apparent for DCP tests, and a normal PDF may be used.

The OMC is an important reference parameter for construction but is of lesser importance to the EMC for volumetrically active clays. Compacted clays (in embankments) have a higher swell potential than undisturbed clays at the same moisture content and density. Pavement design should be based on the EMC rather than a CBR value at the OMC. For non-expansive and /or climates with 500mm to 1,000mm of annual rainfall, the EMC ~ OMC. In dry or wet climates, the EMC governs the design and pavement performance.

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