Material subgrade variability in site characterisation

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ABSTRACT

Delineation of areas into a "uniform" harvestable quality material is required for cut and fill earthworks projects. Mixing or inadvertent contamination with onsite high-quality material with adjacent poor quality is unacceptable. Importing material from off-site sources have significant cost associated. Two case studies are presented to highlight the design and contractual interpretation of a "unform" site.

The first case study compares when a characteristic design value is used versus the day to day on site requirements to meet these design requirements. The required coefficient of variation (COV) of material parameters is discussed from both a design and construction perspective for section delineation. A major highway road widening had 4 sections as part of the upgrade. The tender documents were based on balanced cut to fill. On site material variability had pockets of good and bad material. Statistical analysis pre and post tender were compared in the contractual dispute which followed. The contractor was obligated to then import material to significant subgrade depths for these sites. To do otherwise would be contra to both the design material requirements specified in the contract documents and the requirements of the Earthworks specifications.

The second case study is for a major 13 km rail upgrade to illustrate how the COV can be used in site characterisation and spatial variation at a cutting. The COV values adopted for both design and construction assessment are different as the intent is different. A quality control COV is different for a characteristic design COV.

Keywords: CBR; subgrade; coefficient of variation; site characterisation; remove and replace

1. Introduction

The subgrade California Bearing Ratio (CBR) test is used as one of the inputs in pavement design. The CBR laboratory model needs to be appropriate to the field CBR – this may involve considerations of soaked vs. unsoaked CBR, equilibrium CBR and levels of compaction achievable. In dry climates (< 500mm annual rainfall) and with good drainage an unsoaked CBR may apply (Look, 2022). In wet climates (> 1,000mm annual rainfall) and poor drainage conditions, a soaked CBR test may apply for design.

Consideration must also be given to the variation over the alignment and suitable uniform design sections established. Spatial variation for both the horizontal and vertical alignment affects this CBR input. Two case studies are used to compare the lower characteristic value (LCV) design versus the day to day on site requirements to meet these design requirements.

A design value is typically a moderately conservative subgrade value and interpreted as the 10^{th} percentile value for major road and rail subgrades, although often not specifically stated. The median is the expected value. Contracts are often based on a cut to fill balance with site won material. This would be representative of the median (typical) value across the site. Yet the design value is not the typical value. Understanding both the typical value and the spread of results is required.

The required coefficient of variation (COV) of material parameters is discussed from both a design and construction perspective for section delineation.

These case studies provide a background on when site material variability is acceptable for on site assessment. For non-uniform sites, delineation of areas into harvestable quality material then becomes a lot-by-lot decision process with an associated day by day approval required and is impractical. Quality material interbedded or between areas of sub-standard material is problematic. Mixing or inadvertent contamination with onsite high-quality material with adjacent poor quality is unacceptable. With poor quality or non-uniform sites, improvement or importing material from off-site sources is carried out with significant cost associated.

Case study 1 was for road widening sections along a major highway. Statistical analysis was carried out pre and post tender test values in the contractual dispute which followed. This assessment involved:

1. Relevance and adequacy of pretender data
2. Comparing pre and post tender data
3. Quality. Conforming and non-conforming material assessment
4. Site variability. The COV was used to assess between uniform and non-uniform sites.

During construction, the contractor imported material to significant subgrade depths for these sites, and also with removal of unsuitable materials. To do otherwise would be contra to both the material requirements specified in the contract documents and the requirements of the earthworks specifications. Yet the tender was based on a balanced cut and fill of subgrade material.

Case 2 case study is for a major 13 km rail upgrade and is used to illustrate how the COV can be used in site characterisation.

The COV values adopted for both design and construction assessment are different as the intent is different. A quality control COV is different for a characteristic design COV.

The assessment was undertaken using both box and whisker plots and probability density functions (PDF).

Figure 1 shows the key elements of the box and whisker statistical analysis of the test results. Whisker extends to 1.5 interquartile range (IQR) and would represent 99.3% of results. Mild outliers are data which plots between 1.5 IQR and 3.0 IQR while extreme outliers are greater than 3.0 IQR from the edge of the box.

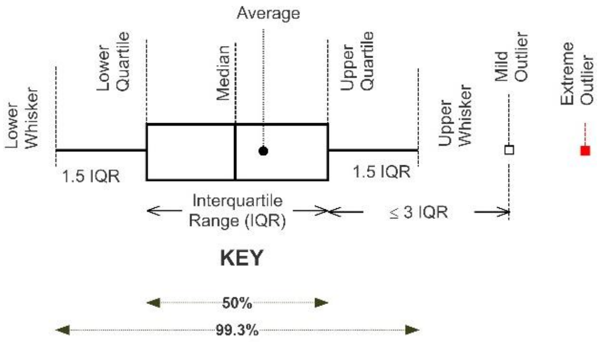

Figure 1. Key describing Box and whisker plot elements.

1.1. Background for material acceptance

Geotechnical material parameters typically have a large COV (Standard deviation / mean) as compared with man-made materials such as steel or concrete. A COV of 20% for concrete is considered poor (Phoon and Kulhawy, 2008) while in soil and rock materials such a strength result would be considered unusual and values of 40% typical. The seminal paper by Phoon and Kulhawy (1999) evaluates geotechnical property variability and is considered a practical guidance for input in reliability-based analysis.

COVs of 90% are common for strength index tests such as CBR (Look, 2009) or Point Load index tests (Look and Wijeyakulasuriya, 2009).

For these case studies a best fit PDF was assessed using a goodness of fit test. A normal PDF can often provide negative and nonsensical values when geotechnical parameters are analysed statistically. A normal PDF does apply to density measurements or other tests which have a low COV (Look, 2015). When a COV above 25% occurs in geotechnical testing, a normal PDF is unlikely to apply (Look, 2015),

Look (2022) states that a large COV of 80% in CBR assessment can lead to contractual disagreements due to material variability The testing variability of CBR is known to be 17% to 58% (Lee et al., 1983). Thus, material uncertainty begins at 58%. Additionally, material won from site would need:

1. To be of suitable quality. This requires satisfying the material specifications.
2. In a winnable quantity (at least 500 m^3 which is typically the minimum lot size). Pockets of “good” material surrounded by poorer quality of material cannot be won without contamination. Minor mixing of poor with good material in bulk earthworks contaminates the good material.
3. Must be in horizontal layers not exceeding 10% grade. Good quality material in a dipping layer is not winnable as bulk earthworks equipment must operate within that 10% grade and unable to chase narrow or dipping layers. This is only able to be directly assessed during construction.

The CBR for this case study was based on a 4-day-soaked test at a target density of 97% density ratio and 100% optimum moisture content (OMC). There were other classification requirements on fines and a weighted plasticity index (WPI) less than 1200. An Emerson Class Number (ECN) > 3 was required.

These other tests are not discussed further, although there were also contractual issues associated with the pre and post tender test results. Section 3 is not discussed in this paper for brevity.

2. Case 1 – Road widening of sections of major highway

2.1. Background – Case 1

Four sections of road widening were required as part of a major road upgrade project in Queensland Australia. On site construction issues occurred due to material variability with pockets of good and bad material. In bulk earthworks, with cut to fill, and with marginally acceptable materials, mixing of material occurred with onsite dispute on acceptable quality.

Accurately delineating where the conforming material started and stopped was challenging and introduced an unacceptable risk should non-conforming material be placed from cut to fill, although cut to fill was the basis of the tender and imported material comes at significant costs.

Additionally delays of up to 4 weeks to sample, test and receive laboratory samples was not practical and time consuming with site equipment stand down times as the sections were not constructed concurrently.

2.2. Site Conditions

The 4 upgrade sections were spread over a 65 km length of the highway. The final design chainages differed from the pre-tender chainages. The latter is shown in brackets below:

1. Section 1: 1.9 km length (6.5 km)
2. Section 2: 1.6 km length (2.7 km)
3. Section 3: 1.5 km length (1.6 km)
4. Section 4: 1.5 km length (5.5km)

Geotechnical test data (over 2,000 pages) was provided to the contractor as part of the tender information. All sites were located in “recent” tertiary and quaternary geology, The materials were classified a clayey sand (SC) and low plasticity clays (CL) pre-tender. The post-tender tender results showed 3 of the 4 sites were classified as high plasticity clays (CH).

A subgrade design CBR was specified on the drawings and contract documents with a subgrade treatment of the natural material requiring remove and replace (R&R) to a specified depth

A summary of the specified properties is summarised in Table 1. The 10%, 25% (quartile) and median value will be analysed. These properties are then compared to measured values pre and post tender for each section.

The depth of treatment of natural material would represent material to be replaced if the design value were not obtained. The specification has no clear guidance on this matter, but the expectation would be for partial replacement if 25% to 10% of subgrade test results falls below that value.

Over 25% of tests below the design value would be considered "full replacement". Note this is not stated but a practical number used by the author.

Table 1. Subgrade design properties required

Material property	Sect. 1	Sect. 2	Sect. 3	Sect. 4
Subgrade Design CBR (Natural – 1500mm)	2%	2.5%	2.5%	3%
0 – 150 to 300 mm below subgrade level (treatment)	10%	10%	10%	10%
Depth of treatment – natural material	3%	3%	3%	3%
Depth of treatment Other treatment as directed on site	200 mm	150 mm	150 mm	300 mm

2.3. Methodology

The key elements relevant to this assessment pre and post tender are:

1. Relevance and adequacy of data. Was data provided for the relevant final design location?
2. Material properties over the relevant chainage. Are these properties consistent for the data provided?
3. Quality and variability for use and reuse. Given the site data was the material suitable for use and in suitable quantity?
4. Specification annexure requires subgrade treatments at each of the site. Given the site data was this treatment carried out? Compliance with the "Earthworks" specification. Were obligations of specification met by the contractor?

2.4. Section 1

The CBR data pre and post tender is provided in Figure 2. Pre-tender testing occurred over 6.50km but the final design is just 1.87 km. This shows data "noise" with 71% of results provided to tenderers is not relevant to the project chainage at section 1. However, when pre and post data is analysed, the box and whisker plots do not show a significant difference for the soaked CBR test results as shown in the box and whisker plot in Figure 3.

The site has a COV = 86% for the post tender results (Figure 4). The assessment shows:

- Pre and post tender data values are broadly similar.
- Data within and out of chainage. Assuming tenders would have the insight to notice there is irrelevant data provided. Values are broadly similar.
- The normal PDF is state of practice expected of industry, but other advanced PDFs are used by specialist engineers. Depending on all data or on chainage data, there would be 68% to 79%, respectively, of the site having a CBR of 10% as required by the contract documents

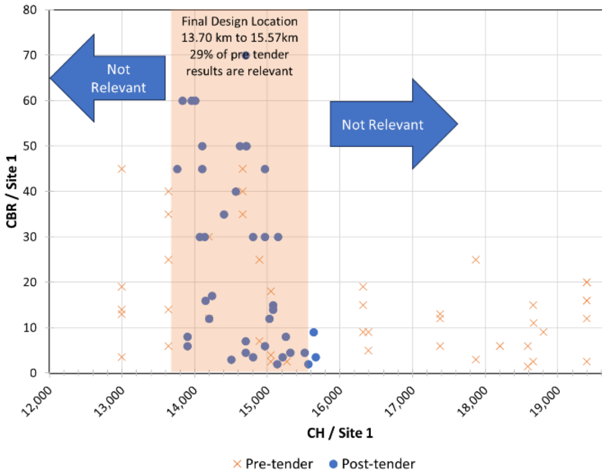

Figure 2. CBR data at site 1 pre and post tender and compared for the final chainage location

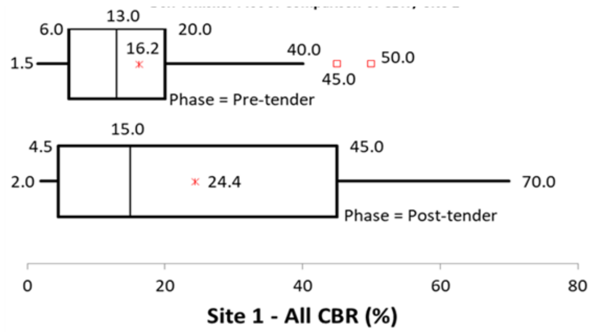

Figure 3. Box and whisker plots for CBR data 1

Projects evolve from planning to preliminary and detailed design. Data acquired from a planning stage may not be relevant to a detailed design. Providing all information to tenderers is the usual practice but creates data noise. Figure 2 was carried out in forensic engineering during a dispute and would not have been apparent to tenders who have very limited time to make their submission.

Post tender and using a more advanced and better fit Log-normal PDF, the availability of CBR 10% and above is reduced to 60% of site 1 (Figure 4). The Log-normal is a better predictor as determined by goodness of fit tests on the site data if the input data is compared. The normal PDF would incorrectly predict 9.3% of values between CBR 3% and 10% while the actual number tested is 32.5% of the CBR test results.

The delineation of discrete materials within cuttings for re-use would be difficult to assess due to its large COV. Based on the variability of the CBR test results, this section is not considered to be a "uniform" site, yet there is quality CBR material available.

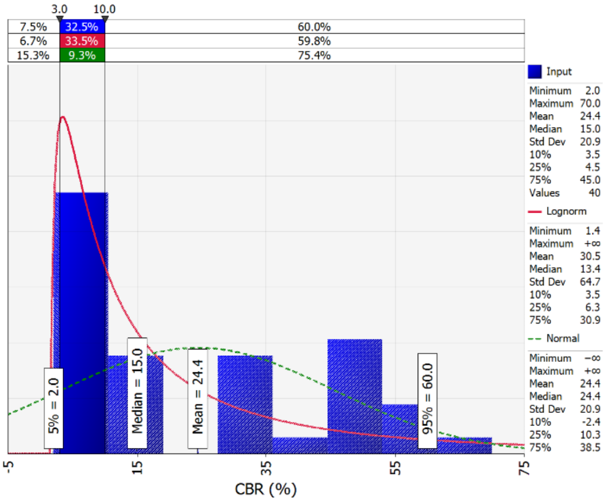

Figure 4. Site 1 CBR data post tender showing normal and Log-normal PDF and actual data

2.5. Section 2

The CBR data pre and post tender is provided in Figure 5. The pre-tender testing was over 2.71km but the final design was just 1.60 km. This shows 41% of results provided to tenderers are not relevant to the project chainage at section 2.

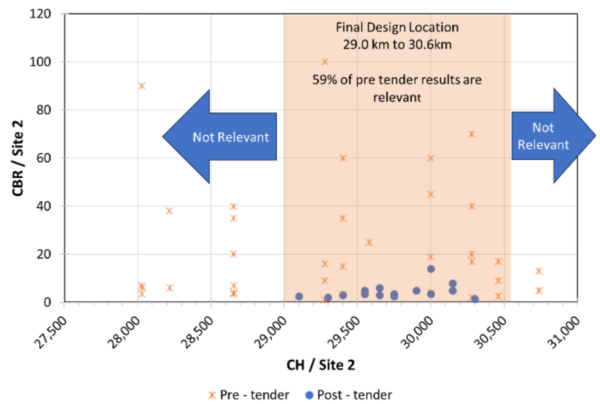

Figure 5. CBR data at site 2 pre and post tender

When pre and post data is analysed, the box and whisker plots show a significant difference for the soaked CBR test results (Figure 6). At site 2 the pre-tender test results suggest 64% of values above CBR = 10%, while post tender testing results show only 6.7% of test results would meet that value which has been specified to the contractor on the drawings (Figure 7). The median test results values were 15% and 3.5% pe and post tender.

With such a change in CBR test results, (% fines and WPI not shown) such differences would be visually evident on site.

With only 6.7% of CBR > 10% quality material on this site 2, the contractor would be obligated to import off-site material. Even if the contractor had the insight to remove the 41% of irrelevant data from consideration pre-tender, the CBR test results would still not be representative.

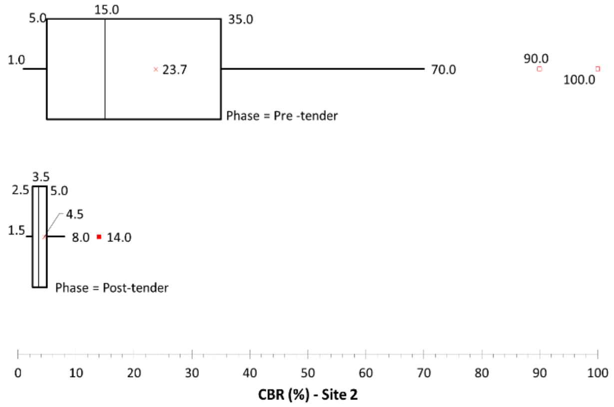

Figure 6. Box and whisker plots of CBR data at site 2 pre and post tender

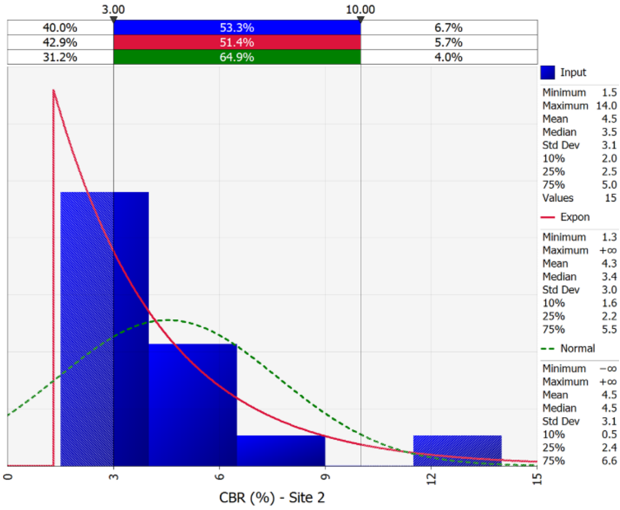

Figure 7. PDF of CBR data at site 2 post tender

2.6. Section 4

The pre-tender testing was over 5.52km but final design was just 1.53 km (Figure 8). Therefore 72% of chainage data provided is irrelevant with 79% of data outside the final chainage at section 4. The difference in values should also be visually evident pre and post tender at the final design location.

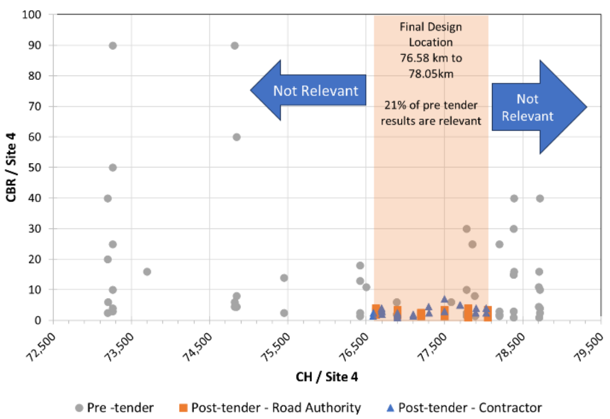

Figure 8. CBR data at site 4 pre and post tender

Given there was both independent testing by the road authority and the contractor post tender, that data was compared and shown in Figure 9. The road authority test results post tender aligns with the contractor results and are different from the pre-tender information provided.

The pretender results show almost 50% of the site 4 would have CBR 10% available. This changes to less than 1% for both sets of post tender test results. This shows ALL of the CBR 10% specified on the design drawings would have to be imported.

The pre-tender results show 33% (on chainage only) of material tested below CBR = 3%. The post tender test results show 70% of the site has a CBR < 3%. This increases the quantity of subgrade treatment and replacement, with little CBR = 10% material available on this site 4 and the earth fill requirement is for CBR = 3% (minimum). Thus, the design requirement has not been met unless material is imported.

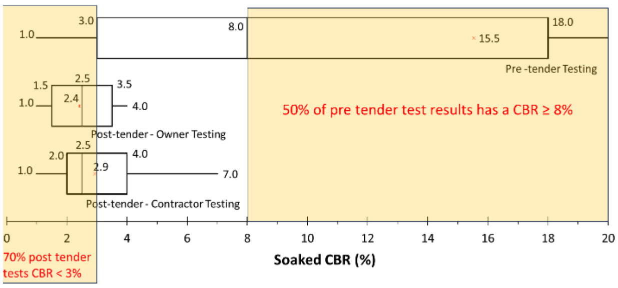

Figure 9. Box and whisker plots of CBR data at site 4. Only CBR values up to CBR 20% are shown for clarity

Pre-tender CBR test results provided had 70% irrelevant as these were outside of the final design chainage. However, the results are comparable when such irrelevant data is removed to be on the design chainage only. The pre-tender and post tender results are vastly different.

Based on the low CBR test results for 70.2% of site test data, (Figure 10) this section requires that local materials be not used. Importing material is necessary to meet the design requirements.

2.7. Discussion of results

A statistical analysis of pre and post tender laboratory testing results has been carried out. Site 3 and the WPI, ECN and % fines results were not presented in his paper for brevity,

As a baseline for comparison, a "uniform" section would have a CBR with a COV < 60%. Above a COV = 80% a site is considered non uniform and open to interpretation. Overall, sections 1 and 3 have a large COV. The COV for CBR in each of the sections was greater than 50%, in some areas both pre and post tender, with sections 1 and 3 exceeding 100%. The pre and post tender comparison shows:

- Site 1: There is adequate on-site material for use as evidenced by pre and post tender data. Some materials were marginal. Given high variability, judicious use of such on-site material is required. Mixing of good and bad material typically results in contamination of good material. With high COV =86% for the CBR, the expectation is that 3 engineers on site will likely have 3 different opinions.

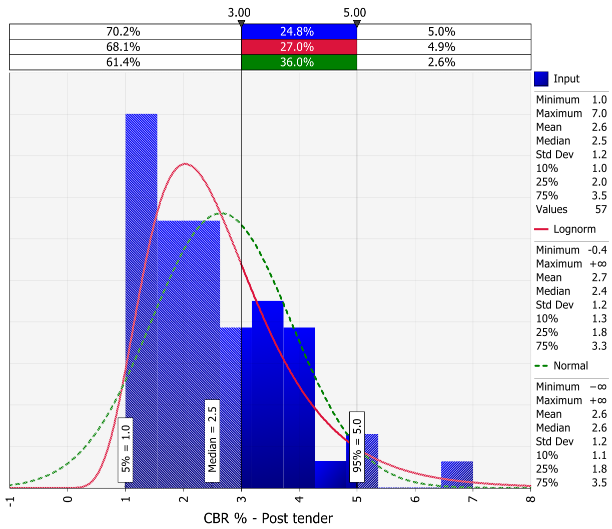

Figure 10. PDF of CBR data at site 4 post tender

- Site 2: COV = 69%. There is significant change in material classification and strength as seen from the pre and post tender data. This site is near uniform. Material quality does not meet the requirements of the drawings, annexure, and specifications. Significant remove and replace (R &R) with imported material would be required to meet the quality standards obligation.
- Site 3: There is significant change in material classification and strength as seen from the pre and post tender data. This site is highly variable. Material quality does not meet the requirements of the drawings, annexure, and Specifications. Given the variability and low-quality material, there is mandatory remove and replace with imported material to meet the quality standards obligation and to significant depths.
- Site 4: There is significant change in material classification and strength from the pre and post tender data. This site is uniform and is the worst of the 4 sites in terms of the material quality and availability. Thus, site 4 is considered uniformly poor quality and does not meet the requirements of the drawings, annexure, and specifications. This leads to mandatory R & R with imported material to meet the quality standards obligation and to significant depths.

At tender stage assumptions on material availability on site based on tender data for sites 2, 3 and 4 would be not representative. Pre-tender data shows a large quantity of CBR > 10% material is available, with only minor areas with CBR < 3% (which needs to be improved).

Post tender site data by both the road authority and contractor shows the opposite of the pre-tender data i.e., large areas of CBR < 3%, and with minor areas of CBR > 10%. This should be self-evident on site.

A contractor is obligated to import material to significant subgrade depths for these sites. To do otherwise would be contra to both the CBR requirements specified in the contract documents and the requirements of the "Earthworks" specifications.

Site 1 material did not satisfy all specification requirements being met for 75% of material tested. Mixing or inadvertent contamination with onsite high-quality material with unacceptable material has a high-quality risk associated for non-conformance of the end product (if audited). This is compounded with high variability at site 1, hence delineation of areas into harvestable quality material would be a lot-by-lot decision process with an associated day by day approval also required.

Figure 11 compares the 4 sites in terms of conforming and uniformity. This case example is used to show how contractual issues arise when uniformity of material and irrelevant data is provided. A typical clause of "it is the responsibility of the contractor to make their own assessment" does not take away the responsibility of providing relevant and accurate site data to contractors.

However, the technical aspects are just one aspect of contractual disputes.

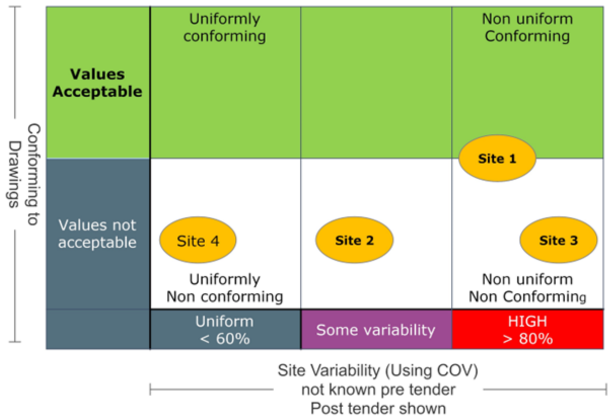

Figure 11. Sites conforming to contract documents and statistical assessment of site variability.

3. Case 2 - Rail line upgrade

This case study is for the assessment of a 13km length of a rail alignment using the results of soaked CBR testing in the preliminary design phase (Look, 2015). The design lower characteristic value (LCV) is compared for various reliability levels and distribution functions.

3.1. Defining sections based on CBR data

The terms percentage defective used in roadways is synonymous to the % fractile or LCV. Variation would also occur both in testing at a specified location and spatially for a given project. Reliability is often discussed in codes and design procedures. For roads reliability design typically allows defects as follows:

- 90% reliability for major roads: i.e. 10% of test values less than the specified value.
- 70% reliability for minor roads i.e. 30% of results defective

A lumped approach using all test results combined shows a COV of 90% over the route. This is very high but even when assessed as design segments a COV of 50% was the lowest calculated value (Figures 12 and Table 2).

Using a normal PDF, a CBR of -5.4% and -1.7% applies at the 5% and 10% fractile, respectively. This negative value is not an error but calculated when a normal PDF is used.

A lognormal or best fit Pearson V PDF, results in a CBR of 3% at the 10% fractile.

At the 5 % fractile the CBR value is unrealistically negative if the normal distribution is applied for all data or for design segments, and even in most 10 % fractile. The best fit and log normal distribution provides comparable values. At the 25 percentile defects, the best fit, the log normal and normal are comparable for the LCV in all cases. This observation is comparable to the point load index best fit PDFs previously discussed

Table 2. Results of distribution models at 10% and 25% risk for the various CBR zones.

Chainage	**All 13km**	**3.5 km**	**1.5 km**	**3.5 km**	**4.5 km**
No. of Values	96	31	6	38	21
COV	90%	72%	50%	101%	71%
LCV & PDF	**Soaked CBR (%)**				
10% LCV					
Best fit	2.9	3.0	15.0	2.3	4.0
Log – Norm	2.8	3.0	14.8	2.2	4.0
Normal	(-1.7)	0.7	10.6	(-2.8)	1.3
25% LCV					
Best Fit	4.6	4.2	18.8	3.8	6,5
Log – Norm	4.6	4.2	18.,7	3.7	6,5
Normal	4.5	4.4	19.6	3.2	7.1

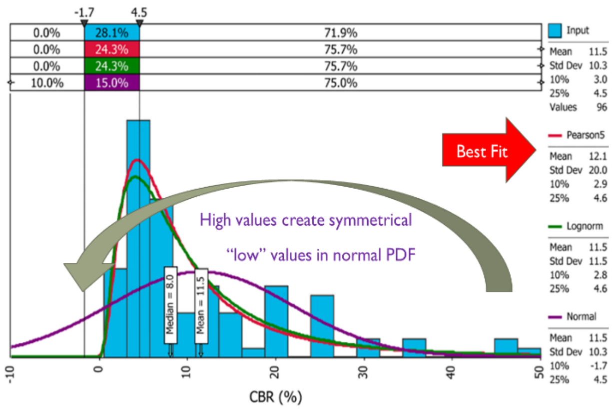

Figure 12. Statistical distribution models for the full 13km length of the site.

Figure 12 is annotated to show the common error that results from using a normal PDF. In analysis, high values create "low" values due to the symmetry in a normal bell curve. The low values may even be calculated as negative as shown in this case, which cannot occur in reality. One must be wary in using a normal PDF when a COV exceeds 25% (Look, 2015).

3.2. Spatial variation in a local cutting

During detailed design further refinement was required. The spatial variation of Cut No. 5 is shown with a yield of 31,000 m^3. Figure 13 shows a cutting where it was proposed to use a CBR 10% as the upper subgrade embankment fill (Look, 2022). Using CBR 10% at the subgrade level would have significant benefits in relation to the capping layer thickness and in the importing of the material (also called sub-ballast). Stockpiling this CBR 10 material for later reuse would have cost benefits.

However spatial variation occurs in many cuttings as shown in Figure 13. While there is a financial benefit to zoning and placing the higher quality material aside for use at subgrade level, care must be taken to ensure the mixing of material does not occur. Mixing in-situ material (unintentionally in this case) failed to provide an improved quality. The CBR > 10% (brown colour) mixed with CBR ≤ 5 (blue colour) occurred during construction.

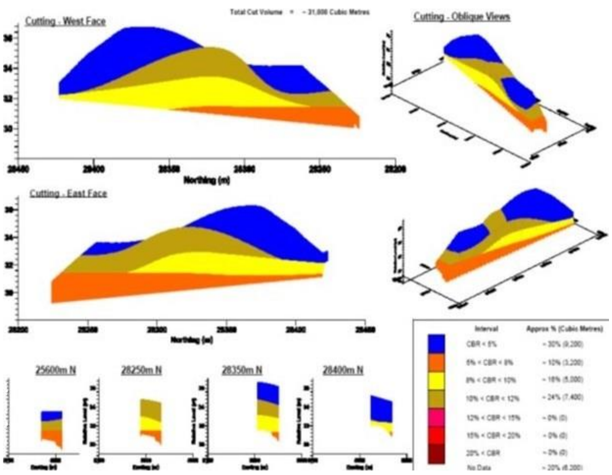

Figure 13. Spatial variation of cutting

4. Discussion and Conclusion

Two case studies were used to show

- The application of statistics in design and construction
- What is a "uniform" and non-uniform site
- The limitations of a normal PDF when using CBR data.

Comparisons were shown between a normal PDF, log normal PDF and best fit PDFs. When COVs are greater than 25%, a normal PDF is unlikely to be the best fit PDF. The lognormal PDF, although not always the best fit, provides a more meaningful prediction of the site variability.

Figure 14 combines the data from the 2 case studies presented in this paper. For this CBR data, a normal PDF would not have prediction errors at or below a COV = 40%. As the COV increases from 60% to 80% the % of negative (and invalid) predicted values are 5.6% and 10.8%, respectively.

Defining a "uniform" section of a site for both design and construction is a major decision which should anticipate potential contractual issues for a "uniform" section. Natural testing variability for CBR is typically 40% and could be up to 60%. Thus, sectioning based on CBR should have this COV as a considered factor.

Sections with a COV > 80% is considered non uniform and likely to have contractual disagreement. Accurately delineating conforming material introduces an unacceptable risk should material be placed cut to fill, although this earthworks balance may be the basis of the tender. Inadvertent mixing from non-uniform material contaminates the high-quality material. Imported material may come at significant costs.

Mixing of material often occurs in bulk earthworks with testing of the resulting material having the result closer to the weaker material used.

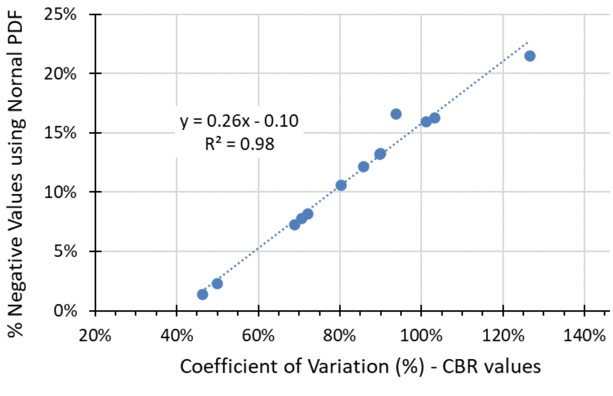

Figure 14. COV compared with the negative values of the normal PDF (if used)

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