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Surcharge design using a probabilistic framework

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ABSTRACT: Long-term settlement performance of airport infrastructure is an important design consideration in sites situated in near-normally consolidated clay deposits. At the Brisbane Airport, post-construction settlement is heavily dominated by secondary compression (or creep) characteristics of the clay and the clay thickness. The ground improvement strategy adopted for the New Runway project comprised site surcharging with and without wick drains. The client had defined the post-construction settlement criteria as non-exceedance at the 95%ile confidence level. Therefore, our design was undertaken in a probabilistic framework to inform the range of post-construction settlements. The probabilistic framework was established using a detailed site investigation and laboratory testing program. And the results produced a range of settlement outcomes which are a function of the range in input variables. The results of the analyses were used as part of the Observation-al Method.

1 INTRODUCTION

Long-term settlement performance of airport infrastructure is an important design consideration in sites situated in near-normally consolidated clay deposits.

Surcharge design in a probabilistic framework was undertaken for the New Runway project at the Brisbane Airport in Queensland, Australia. The 360 ha site is underlain by weak and compressible clay deposits which require ground improvement prior to the construction of sensitive infrastructure.

The investigation and design was completed in 2011 and construction on the reclamation works commenced in 2014.

1.1 Site setting

Like many airports around the world, Brisbane Airport is located in a coastal setting, within the Brisbane Delta. The soil profile consists of Holocene alluvia overlying, older Pleistocene alluvia, which in turn overlies Tertiary age basalt bedrock associated with the Petrie Formation.

The Pleistocene layer comprises over-consolidated stiff to hard clays and medium dense sandy/gravelly material which are relatively incompressible. Holocene clay deposit is the main geotechnical issue at the Airport because of its weak and highly compressible nature. This deposit is generally highly variable in depth and extent, and clay

thickness in the order of 25 m (single layer) has been encountered. Figure 1 illustrates the site plan and runway layout with the inferred contours of base elevation of compressible alluvial soil. The red shaded area in Figure 1 indicates an area where the compressible alluvial soil extends deeper than RL-20 m Aerodrome Datum (AD). The properties and thickness of the lower Holocene clay typically dominate settlement behaviour at the Brisbane Airport.

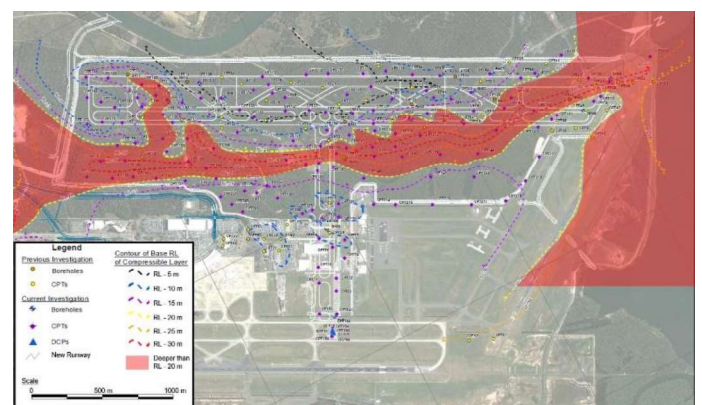


Figure 1. New Runway project - Inferred contours of base elevation of compressible alluvial soil.

2 SITE SURCHARGING AND METHODOLOGY

2.1 Design considerations

The post-construction settlement (in-service) design criteria for airport infrastructure is stringent due to the critical nature of the infrastructure and restrictive

operational constraints should remedial actions be required. At the Brisbane Airport, post-construction settlement is heavily dominated by secondary compression (or creep) characteristics of the clay and the clay thickness. Secondary compression alone can easily exceed the post-construction design criteria due to the relatively thick clay deposits.

The ground improvement strategy adopted for the New Runway project comprised site surcharging with and without wick drains. Other ground treatment options were explored however site surcharging with wick drains was deemed to be the most cost-effective solution for this site.

A fill source was identified comprising dredged sand from the Morton Bay Middle Banks to form the runway and taxiway embankments and surcharge material. About 11 million cubic metres of sand has been dredged for the project. The dredged sand is relatively homogeneous, uniformly graded, with less than 5% fines content (passing the 75 μm sieve). The same fill source has been used in previous developments at the Brisbane Airport and dredged in the 1980s to form the existing runways, taxiways, apron and terminal platforms.

2.2 Settlement analysis methodology

The settlement analysis was carried out using Golder's in-house software, PCON Version 4.1. PCON calculates primary consolidation settlement using consolidation theory and a sub-layer formulation of Terzaghi's equation for one-dimensional pore pressure dissipation. Primary consolidation pore pressure dissipation with time for each sublayer and timestep is calculated using the Terzaghi approach. The corresponding primary consolidation settlement (or vertical strain increment) is calculated from the idealized 1-dimensional vertical strain vs. $\log \sigma_v'$ curve in the classical way, using the $C_c/(1+e_0)$ slope for the virgin portion and the $C_r/(1+e_0)$ slope for the unload-reload portion.

Normally consolidated (virgin) secondary compression is computed using the log-time rule from 90% of that for the completion of primary consolidation. Secondary compression for over-consolidated conditions is computed using a log-time rule time base transformation based on the current Over Consolidation Ratio (OCR), as incorporated in the Delft PLAXIS finite element code's Soft-Soil (i.e., Cam Clay creep) model.

2.3 Probabilistic framework

The compressible soils on the site would be expected to have some variations in consolidation characteristics due to inherent variations in material type, loading history, deposition, etc. Traditionally,

our design would be carried out using deterministic analysis and sensitivity analysis being carried out at selected locations to identify possible upper bound outcomes. In this instance, the client had defined the post-construction settlement criteria as non-exceedance at the 95%ile confidence level. Therefore, our design was undertaken in a probabilistic framework to inform the range of post-construction settlements.

In order to estimate the likely variation in post-construction settlement behavior as a result of these variations, probabilistic analyses were carried out using PCON in conjunction with the commercially available software @RISK Version 5.5. @RISK uses a Monte-Carlo simulation approach to calculate the values of settlement at different confidence levels. Distribution of input parameter values were defined for various consolidation input parameters. The @RISK program provided probabilistic results for selected model outputs, in particular settlement at the end of surcharging (to inform fill re-handling volumes) and post-construction settlement, across 1000 iterations.

The selection of geotechnical parameters is a key design consideration in the surcharge design.

3 GEOTECHNICAL PARAMETERS

3.1 Field testing

The probabilistic framework was established using a detailed site investigation and laboratory testing program.

The field testing comprised 217 piezo-Cone Penetration Tests (CPTs) and 54 geotechnical boreholes (BHs) to characterize the subsurface stratigraphy and groundwater regime. It was important to establish whether the consolidating units had one-way or two-way drainage conditions. Figure 2 illustrates the generalized stratigraphic profile of the Runway alignment.

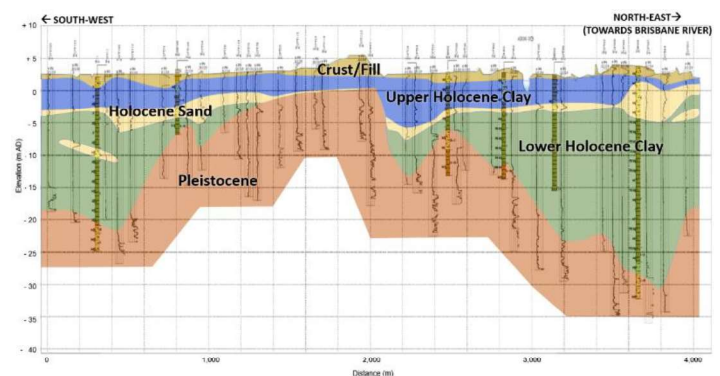


Figure 2. Runway long-section inferred stratigraphic profile.

A total of 38 overnight dissipation tests were also undertaken to assess the horizontal coefficient of consolidation.

Selected CPT locations were targeted for insitu vane shear tests to assess the undrained shear strength and to establish a N_{kt} correlation with CPT results. Figure 3 illustrates the inferred undrained shear strength correlated with vane shear tests using a N_{kt} factor of 15. The vane shear tests have been corrected for Plasticity Index (PI~45%) using Bjerrum's approach (Bjerrum, 1973). This correlation was used to assist in the assessment of OCR from CPT data.

Samples were recovered for laboratory testing. These typically comprised undisturbed tube samples (U63s and U75s).

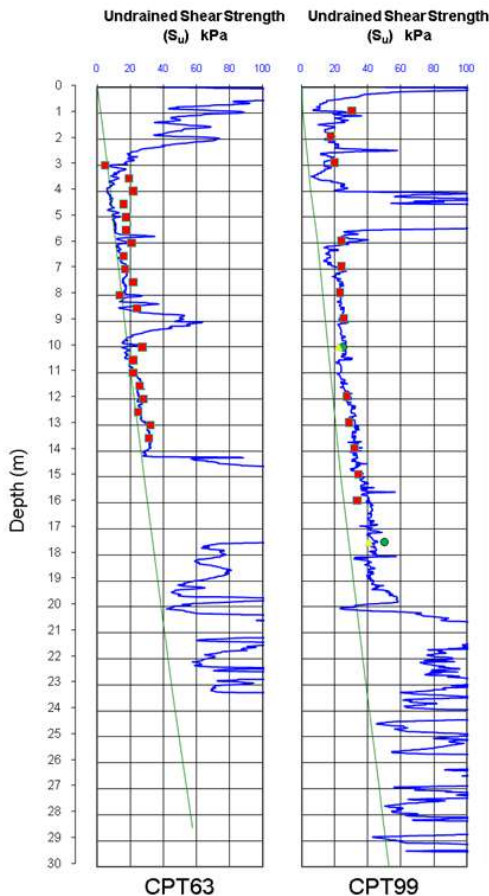


Figure 3. Undrained shear strength – Corrected down-hole vane shear correlated with CPT data using $N_{kt} = 15$.

3.2 Laboratory testing

Laboratory testing was undertaken on selected samples. The samples were tested for their engineering material properties with the following tests: multi-stage oedometer, plasticity, grading, moisture content and hand-vane shear. A total of 63 oedometer tests have been undertaken to inform the detailed surcharge design and this data set was augmented by oedometer test results from nearby sites. Each oedometer was interrogated to derive the following consolidation parameters: compression index (C_c), recompression index (C_r), and Coefficient of Secondary Compression ($C_{\alpha\varepsilon}$). It was identified that the normally consolidated $C_{\alpha\varepsilon}$ had not been sufficiently defined during the 24-hour standard oedometer load-

ing cycle and longer loading cycles were required which were in the order of 48 hours.

3.3 Back-analysis of settlement plates

The adopted coefficient of vertical consolidation (c_v) input distribution was based primarily on the range of field-scale values that were determined from back-analyses at nearby sites.

The surcharge design was carried out for both wick drain and non-wick drain areas. The effect of wick drains has been represented in the modelling by assigning an equivalent value to c_v , such that the time for consolidation of the equivalent 1-dimensional layer is the same as the time for consolidation calculated using radial drainage theory for wick drains (Pilot, 1981).

Wick drain parameters, in particular the ratio of horizontal to smear zone permeability, were back-analysed from 46 settlement plates at nearby sites with wick drains.

In the back-analysis, geotechnical parameters such as bulk density and $C_c/1+e_0$, were selected using values from within the range indicated by laboratory test results. The value of c_v equiv. which gave the best fit to the observed settlement was determined. The value of c_v equiv. for a layer which includes wick drains is governed by the c_v without wick drains, the ratio of horizontal permeability to vertical permeability (k_h/k_v), and the ratio of horizontal permeability to smear zone permeability (k_h/k_s). It was agreed that k_h/k_s as the parameter most likely to vary as a result of variability in the natural materials or variability in the installation methods. The permeability ratio (k_h/k_s) was therefore fixed to an assumed value of 2 resulting in a c_v without wick drains to 3 m²/yr for the lower Holocene clay. Generally, the Upper Holocene clay was not thick enough to adopt a c_v equiv. value greater than its native c_v (without wick drain) value.

Values of k_h/k_v and c_v will also vary somewhat and thus k_h/k_s was used as a surrogate to represent all the factors that lead to variation in the resulting c_v equiv. value. The resulting k_h/k_s histogram from back analysis is presented in Figure 4 and is bimodal in shape. Lower values of k_h/k_s represent observations where wick drains are effective in increasing the rate of consolidation during surcharging. The majority of the settlement plate monitoring data (approximately 80%) indicates that wick drains have been effective in ground treatment with k_h/k_s values in the range of 1 to 16. However, approximately 20% of the settlement plates assessed did not show significant improvement to surcharging, with k_h/k_s in the range of 22 to >30. This observation is consistent with anecdotal evidence that wick drains have been observed to be ineffective in some cases in south-east Queensland (Robertson, 1984; Wijeyakulasuriya et al., 1999).

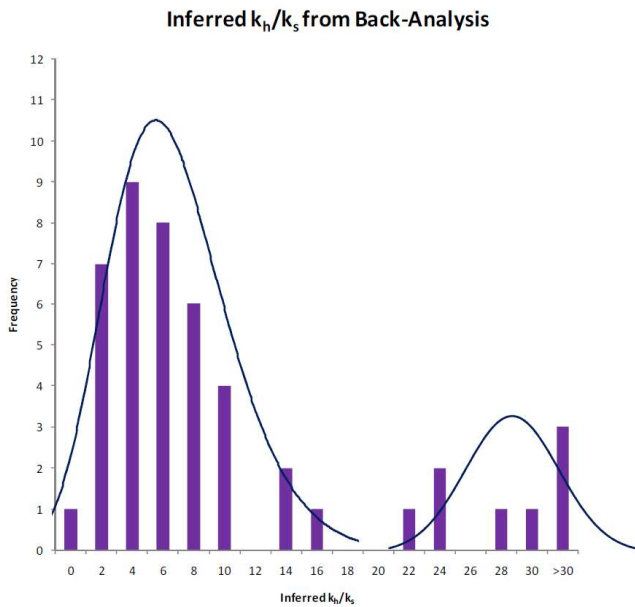


Figure 4. Histogram of Inferred k_h/k_s of Lower Holocene Clay from Back-Analysis of Settlement Plates.

3.4 Parameter distributions

The parameter distributions for Upper and Lower Holocene Clay in Table 1 were adopted in the settlement analysis. The adopted wick drain parameter distributions are presented in Table 2. The numbers shown on the distribution graphics indicate the maximum and minimum values of the input parameters. These input parameter distributions were used in the probabilistic settlement analysis to produce a range of settlement results.

Table 1. Adopted Input Parameter Ranges for UHC and LHC

Parameter	Confidence Level			Distribution
	5%	50%	95%	
UHC: $C_v/(1+e_0)$	0.10	0.15	0.25	
UHC: C_v (m ² /yr)	5	10	20	
UHC: $C_{\alpha\epsilon}$	0.3%	-	1.0%	
UHC: C_v/C_r	5	-	10	
LHC: $C_v/(1+e_0)$	0.15	0.25	0.35	
LHC: C_v (m ² /yr)	1	3	6	
LHC: $C_{\alpha\epsilon}$	0.8%	1.0%	1.2%	
LHC: C_v/C_r	5	-	10	
OCR	Determined by CPT ($N_{kt} = 15, s_u/\sigma_v' = 0.22$)			

The range of values adopted for the Lower Holocene Clay is consistent with the narrow range measured in field CPT dissipation tests. The adopted Upper Holocene Clay range of values was much narrower than the very wide range of measured values from CPT dissipation tests.

The distributions for $C_{\alpha\epsilon}$ were truncated to exclude the influence of some samples that contained a high percentage of sand. Based on limited observations of secondary compression at other sites, it is considered unlikely that field-scale values of $C_{\alpha\epsilon}$ would be lower than the lower limits indicated in Table 1.

Table 2. Adopted Input Parameter Ranges for C_v equiv. using Wick Drains

Parameter	Confidence Level			Distribution
	5%	50%	95%	
WD Width	Product Specific e.g. 100 mm			-
WD Thickness	Product Specific e.g. 3 mm			-
Mandrel Width	Case Specific e.g. 120 mm			-
Mandrel Depth	Case Specific e.g. 60 mm			-
Pattern	Case Specific e.g. square			-
k_h/k_v	-	2	-	-
k_h/k_s (bimodal)	1	14	43	

4 SETTLEMENT ANALYSIS RESULTS AND SURCHARGE DESIGN

The site was zoned for areas that had similar ground conditions and several CPTs were selected for probabilistic settlement analysis within each zone. For a given surcharge duration, the surcharge height was varied until the settlement results satisfied the Post-Construction Settlement (PCS) design criteria. Where surcharging alone could not satisfy the PCS design criteria due to a large thickness of clay, wick drains were introduced and the spacing was varied to comply with the PCS design criteria.

The results form an envelope of possible settlement outcomes based on the input parameter ranges presented above. An example of the settlement vs log-time graph is presented in Figure 5 for a typical area without wick drains and Figure 6 for a typical area with wick drains for surcharge arrangements that satisfy the PCS criteria of the project; with surcharge removal occurring after about 1000 days. Figure 6 (wick drained area) indicates large settlements during the surcharge period compared to Figure 5 of similar surcharge duration.

The key settlement outputs i.e., settlement at the end of surcharging and post-construction settlement were presented at the 5%ile, 50%ile and 95%ile confidence levels. Figure 7 presents a typical output of post-construction settlement after 40 years. The

standard deviation of settlement results is a function of the input parameters. In areas where wick drains were proposed, the range of settlements were skewed to the right due to the model sensitivity to the $c_{v \text{ equiv}}$ parameter.

These settlement outputs and distributions are to be used in the observational method during site surcharging. The settlement plate monitoring data obtained during the surcharge period will be used to compare theoretical predictions with actual behavior.

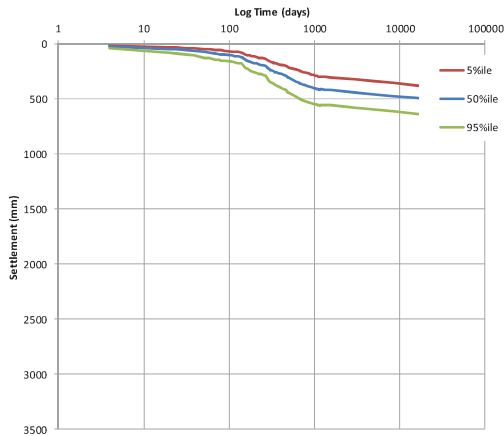


Figure 5. Typical Settlement vs Log Time graph with probabilistic range of settlement results – non-wick drain areas.

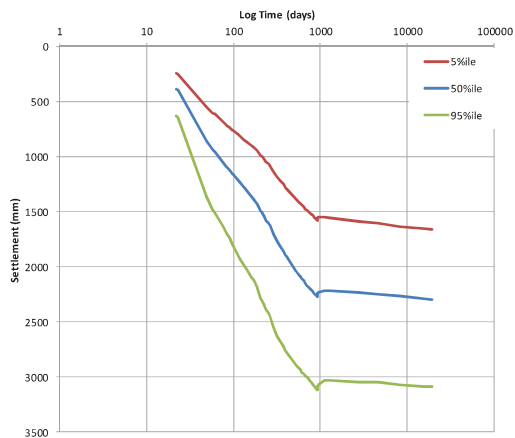


Figure 6. Typical Settlement vs Log Time graph with probabilistic range of settlement results – wick drain areas.

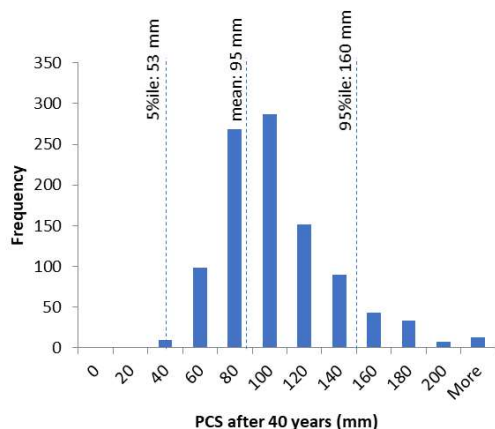


Figure 7. Typical post-construction settlement histogram output.

5 CONCLUSION

The design post-construction settlement criteria defined in probabilistic terms i.e., at the 95%ile confidence level, for the New Runway project. A probabilistic framework for consolidation settlement analysis was established using a detailed site investigation and laboratory testing program. Input parameters and their probabilistic distributions were derived from the results of in situ testing, laboratory test data and back analysis of settlement plates from nearby sites.

The analysis produced a range of settlement results which was used to develop the surcharge design to satisfy the design post-construction settlement criteria.

6 ACKNOWLEDGEMENTS

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