Development of a site-specific correlation for the verification of relative density of dredge reclamation sand fill using CPT results

N. A. Murphy[1], K.R.Biram[2], S.R.Fidler[3]
Golder Associates Pty Ltd, Brisbane, Australia, nmurphy@golder.com.au[1], kbiram@golder.com.au[2], sfidler@golder.com.au[3]

ABSTRACT: This paper provides the methodology and results for the development of a site-specific correlation to verify that relative density (Dr) of sand placed for a large reclamation project was in accordance with specified values. Estimates of Dr were obtained from large scale in-situ density tests, Vertek direct sampling, sand replacement and nuclear gauge density tests. Estimates of Dr from these measurements were compared to estimates of Dr obtained from an extensive Cone Penetration Test (CPT) program, using published empirical correlations to CPT results. The published correlations were developed based on laboratory testing in calibration chambers, using materials that were generally coarser and with lower proportions of quartz than the reclamation sand. The published relationships showed a tendency to significantly over-estimate Dr. A site-specific correlation was hence developed, using an existing published form of correlation. The comparison of CPT test results and direct measurements of density and Dr indicate that there is a degree of uncertainty involved in estimating Dr from CPT test results that should be considered when using CPTs for assessment of compliance with specified density requirements.

Keywords: relative density; dry density ratio; cone penetration test; seismic dilatometer test

1. Introduction

This paper presents an assessment of the sand density using the results of in-situ density tests together with empirical assessment of density using Cone Penetration Tests (CPTs) and dilatometer tests undertaken across the placed reclamation sand for the Brisbane Airport New Runway project.

The initial testing regime to assess the density of placed reclamation sand (comprising sand replacement tests and nuclear gauge density tests) was not providing sufficient confidence that the density required by the Specification had been met. In part this was because the testing undertaken did not provide information across the full depth of placed sand.

An extensive CPT testing program had been completed in the reclamation sand to satisfy other requirements in the Specification, and it was proposed that the CPT data could be used to assess whether the compaction/density requirements of the Specification have been met across the full depth of the placed sand.

2. Reclamation sand properties

A total of 11 million m^3 of sand was dredged for the New Runway project from the Middle Banks area of Moreton Bay. Testing completed on the sand indicated a uniform fine to medium grained clean sand with a d_{50} (50% passing this particle size) of 0.23 mm and a fines content (material passing the 0.063 mm sieve) of less than 3 %. The sand content is dominated by clear quartz and under magnification, the sand grains appear angular to subangular.

3. Relative density assessment

The project Specification for compaction of the reclamation sand required a dry density ratio (DDR) of 90%. In order to determine a relative density value that corresponds to a DDR value of 90%, laboratory tests results for maximum and minimum dry density were utilized. A total of 136 maximum and minimum dry density laboratory tests were completed on sand sampled from the reclamation. The maximum and minimum dry density was determined using AS 1289.5.5.1-1998 (R2016). Fig. 1 and Fig. 2 present the distribution of test results, and the corresponding best-fit normal distribution curves, for the minimum dry density and the maximum dry density values respectively. The fitted normal distribution of test results was assessed using the commercially available software, @Risk Version 5.5 [6].

The minimum dry density results indicated a range of 1.33 t/m^3 to 1.43 t/m^3, with a mean value of 1.41 t/m^3 and standard deviation of 0.012 t/m^3.

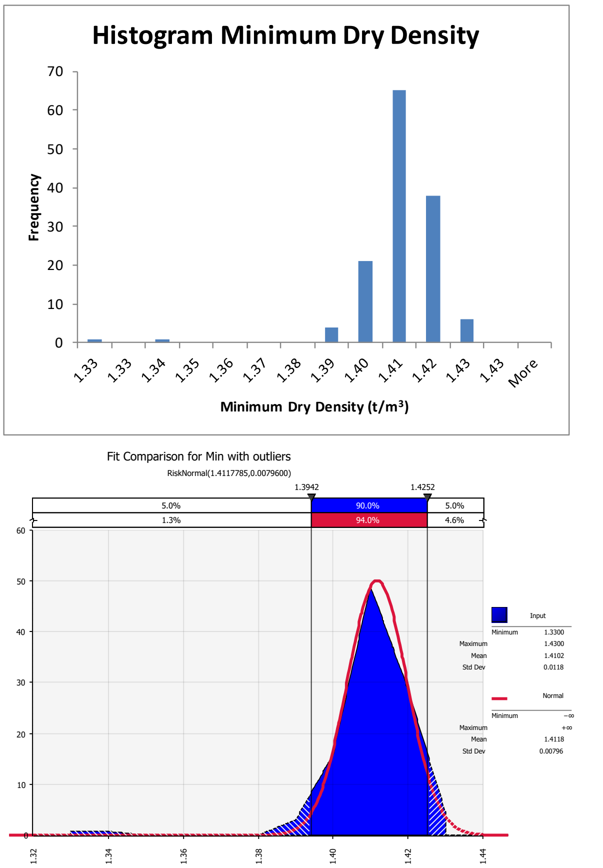

Figure 1. Minimum dry density ratio distribution using @Risk5.5 [6] for all laboratory test data.

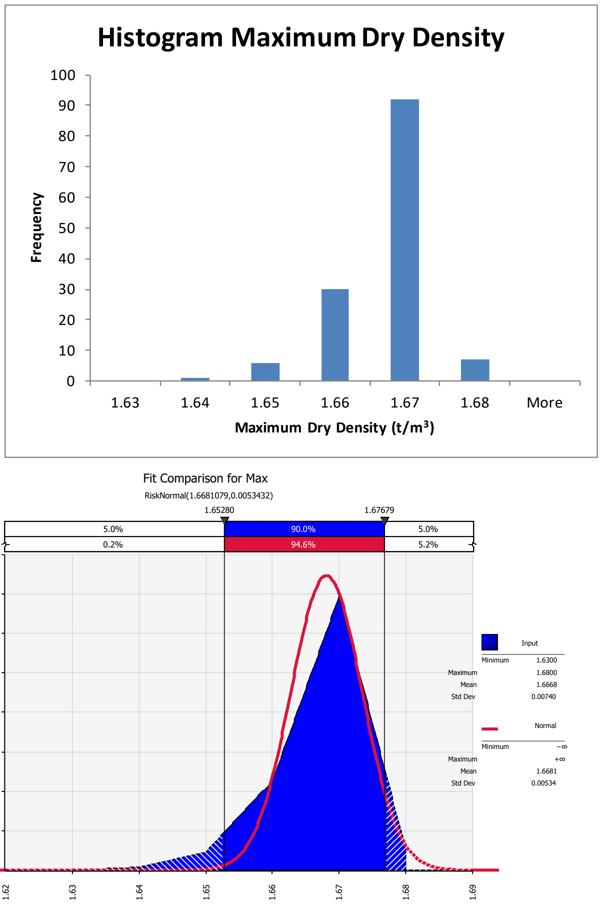

Figure 2. Maximum dry density ratio distribution using @Risk5.5 for all laboratory test data.

There appeared to be two "outlier" values which indicate a relatively low minimum dry density compared to the majority of the test data i.e., 1.33 t/m^3 and 1.34 t/m^3. If these two tests are omitted from the analysis, Fig. 3 presents the distribution of test results and fitted normal distribution curve for the adjusted data (sample size 134). The adjusted distribution has a range from 1.39 t/m^3 to 1.43 t/m^3, with a mean value of 1.41 t/m^3 and standard deviation of 0.008 t/m^3.

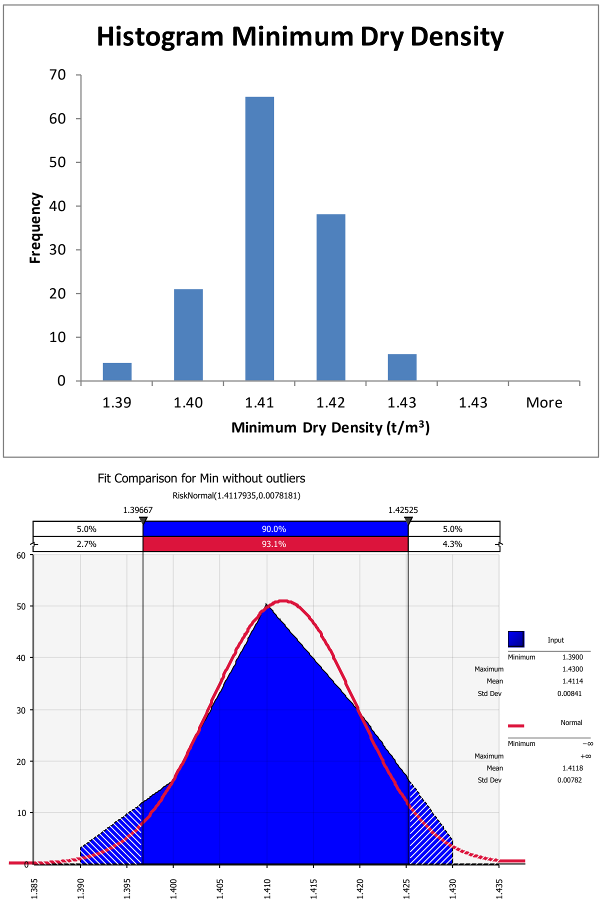

Figure 3. Minimum dry density ratio distribution using @Risk5.5 with two outlier values omitted.

The results of maximum dry density range from 1.63 t/m^3 to 1.68 t/m^3, with a mean value of 1.66 t/m^3 and a standard deviation of 0.007 t/m^3.

Eq. (1) presents the relationship between maximum and minimum dry densities, and the relative density which corresponds to a dry density ratio of 90%.

$$D_r = \left(\frac{\gamma_{90}-\gamma_{min}}{\gamma_{max}-\gamma_{min}}\right)\left(\frac{\gamma_{max}}{\gamma_{90}}\right) \quad (1)$$

, where γ is the unit weight (maximum, minimum and at 90% DDR).

Using @Risk 5.5 [6], values of D_r were calculated using Eq. (1) for 1000 Monte Carlo realizations, with sampling of values for minimum and maximum dry density from the normal distributions illustrated in Fig. 2 and Fig. 3. The distribution of calculated D_r is presented in Fig. 4. The resulting distribution indicates a mean relative density of 38.2% and a standard deviation of 2.8%. The 95th percentile value is 42.5%.

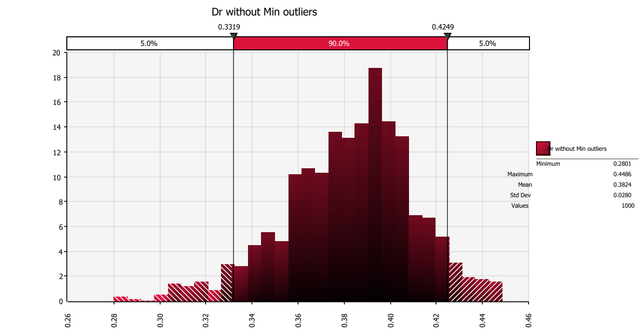

Figure 4. Relative density using input distributions in Figure 3 (with outliers excluded) and Figure 2.

The results indicate that a relative density of 42.5% could be adopted at the 95% confidence level to satisfy the 90% dry density ratio requirement in the Specification.

An alternative way of assessing the relative density is to look at the minimum and maximum dry density "couples" for each of the laboratory test samples. Each "couple" was used in Eq. (1) to produce 136 results for relative density. The distribution for these results is presented in Fig. 5. A normal distribution has been fitted to the results.

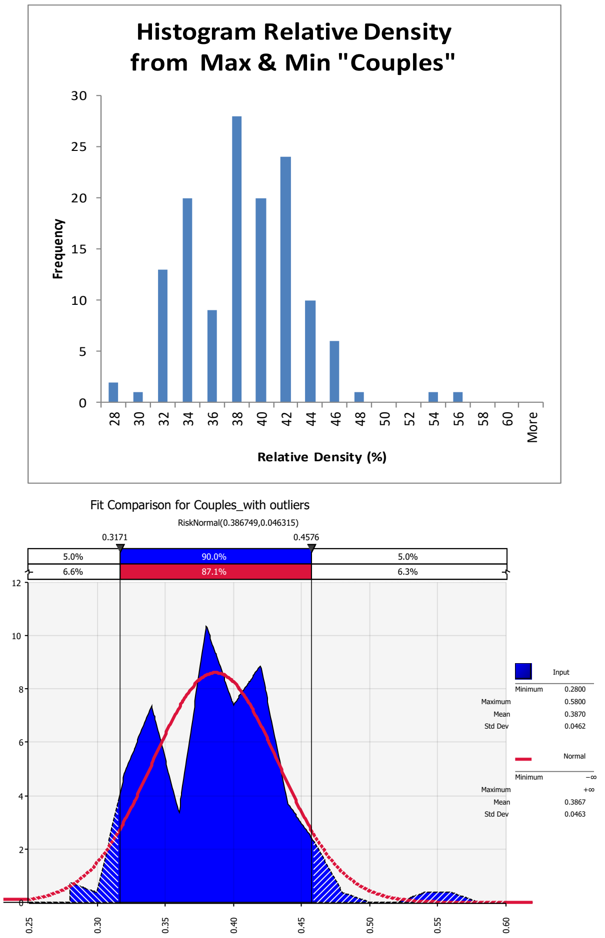

Figure 5. Relative density using maximum and minimum couples using Eq. (1).

Using distribution derived from the minimum and maximum dry density "couples" from each of the test samples, the mean required Dr in order to achieve the specification requirement of 90% DDR is 38.7%. The required Dr at a 95% confidence level is 45.8% (i.e. by setting the requirement that Dr is greater than 45.8 %, there is a high level of confidence that the material complies with the Specification requirement of DDR greater than 90%). These values have been adopted in the current study.

4. *Results of field sampling and testing*

In order to directly measure the sand density to enable a site-specific correlation, the following sampling activities were completed:

4.1. Direct sampling using a Vertek sampler

Four samples were recovered using a Vertek sampler at depths ranging from 1.85 m to 6.34 m below the current reclamation surface, adjacent to three CPT locations (designated CPT_A1_A_22, CPT_B2_A_02 and CPT_B2_A_10), targeting zones of low q_c identified by CPT results. The Vertek sampler was pushed to a depth of 550 mm, and a vacuum was used to assist the recovery of the samples below the water table. Physical samples (of diameter 35 mm) were recovered over a known test interval (and thus, a known volume) and weighed on site. Laboratory testing of moisture content was undertaken in order to allow calculations of minimum dry density. Particle Size Distribution (PSD) testing was also undertaken on recovered samples to assess fines content.

The results are provided in Table 1 below. A total of 10 attempts of sampling were made, however, only four samples were collected with suitable sample recovery.

Table 1. Vertek Sampling Results

Vertex Sample RL (m AD[1])	**DDR[2] (%)**
CPT_A1_A_22 3.15-2.66 (89% sample recovery)	98.5
CPT_B2_A_10 7.78-7.35 (78% sample recovery)	89.8
CPT_B2_A_10 6.13-5.81 (58% sample recovery)	103.4
CPT_B2_A_02 4.82-4.56 (47% sample recovery)	106.9

1. Surface RL is relative to Aerodome Datum (AD)
2. Based on a maximum dry density of 1.66 t/m^3

As full recovery was not achieved in the Vertek samples, the results only provide an estimate of density. It is possible that sample disturbance could result in higher density of the recovered sample due to sand compressing within the sample tube. However, the placed sand is of low compressibility and it is likely that any effects would be insignificant. The length of recovered sample was measured from which densities were calculated.

The calculated dry densities were within the range of 1.48 t/m^3 to 1.76 t/m^3 which are considered to be credible values [4]. Using a maximum dry density of 1.66 t/m^3, which was the average from the density testing of the placed sand, this would equate to dry density ratios in the range of 89.2 % to 106.3 %.

The moisture content of samples recovered varied significantly from 5.1% to 22.8% as samples were taken both above and below the perched water table. The fines content is generally less than 5% except for the sample recovered at CPT_B2_A_02 (4.82-4.56m AD) which results in 11% fines content (passing 75 µm seive). The PSDs indicated similar distributions for all samples recovered.

4.2. Large scale in-situ density tests

Seven large scale in-situ density test were undertaken adjacent to completed CPTs. The elevations targeted a zone of constant but low q_c above the water table. In simplistic terms a 600 mm diameter by 600 mm depth cylindrical sample was recovered and weighed. The excavated void was then lined with thin plastic and filled with water, of measured volume, to allow for an accurate volume measurement of the excavated void. Laboratory testing of moisture content and wet mass was undertaken on the recovered sand sample in order to calculate field in-situ dry density. Some PSD testing was also undertaken on representative samples to assess fines content.

Photos of the large scale in-situ density tests are shown in Fig. 6 to Fig. 9.

Figure 6. Photograph of excavated pit at approximately 2.4 m below reclamation level.

Figure 7. Photograph of 600 mm diameter sample taken for large scale density test.

Figure 8. Photograph of large scale sampling within excavated pit.

Figure 9. Photograph of water replacement test following the removal of sand within the 600 mm diameter sample.

The results of the seven completed large scale density tests are summarized in Table 2.

Table 2. Large Scale In-situ Sampling Results

Sample RL (m AD[1])	Relative density, Dr (%)	DDR[2] (%)
CPT_B2_A_10 7.23-6.63	68	94.5
CPT_C1_A_01 7.31-6.76	56	93
CPT_C1_A_20 7.65-7.10	39	90
CPT_B2_A_21 8.11-7.56	40	90.5
CPT_A1_A_17 6.90-6.35	56	92
CPT_A1_A_25 6.00-5.45	52	92.5
CPT_A1_A_38 6.80-6.25	41	91

3. Surface RL is relative to Aerodome Datum (AD)
4. Based on a maximum dry density of 1.66 t/m^3

4.3. Seismic dilatometer tests

Seismic Dilatometer testing was carried out adjacent to 10 CPT locations using a 15 ton capacity rig. The flat dilatometer is a stainless steel blade (95 mm width and 15 mm thick) having a flat, circular membrane (60 mm diameter) mounted flush on one side. The blade is connected to a control unit on the ground surface by a pneumatic-electrical tube (transmitting gas and electrical continuity) running through the insertion rods. A gas tank, connected to the control unit, supplies the gas pressure required to expand the membrane. The blade is advanced into the ground in depth increments of 20 cm.

Soon after penetration, the operator inflates the membrane and, in about 1 minute takes two readings at each depth increment of: (1) the A-pressure, required to just begin to move the membrane against the soil, and (2) the B-pressure, required to move the center of the membrane 1.1 mm against the soil.

A seismic module is attached next to the membrane to measure horizontal shear wave velocities during the expansion of the membrane at 1.0 m depth intervals. The A-pressure, B-pressure and shear wave velocities are then interpreted using established correlations to obtain a wide range of common geotechnical parameters.

5. Empirical correlations of relative density (Dr) to existing CPT data

The aim of the field sampling and testing activities was initially to match the field results to established relative density (Dr) and CPT correlations by Baldi et al [1] and Jamiolkowski et al [2]. These relationships were developed based on laboratory testing in calibration chambers, for normally consolidated, low compressibility Ticino sands which are clean, fine to medium, uniform sands with about 30 % quartz content. The sand at the New Runway site (from Middle Banks in Moreton Bay) is generally finer than and contained higher proportions of quartz than the Ticino sands; however, these relationships were used initially to determine a nominal value for relative density.

The empirical correlations between Dr and CPT cone resistance q_c by Baldi et al [1] uses the following relationship in Eq. (2):

$$D_r = \frac{1}{C_2} \ln\left(\frac{q_c}{C_0(\sigma'_{v0})^{C_1}}\right) \quad (2)$$

, where q_c is cone penetration resistance in kPa, σ'_{v0} is effective stress in kPa and $C_0 = 157$, $C_1=0.55$, $C_2 = 2.41$.

The empirical correlations between Dr and q_c by Jamiolkowski et al (2001) is of a similar form and adopts slightly different values of the correlation parameters shown in Eq. (3):

$$D_r = \frac{1}{C_2} \ln\left(\frac{q_c/p_a}{C_0(\sigma'_{v0}/p_a)^{C_1}}\right) \quad (3)$$

,where $C_0 = 17.74$, $C_1=0.55$, $C_2 = 2.90$, $p_a=101$ kPa (atmospheric pressure).

Using both the Baldi et al [1] and Jamiolkowski et al [2] correlations, the relative density Dr was calculated at the seven CPT locations, where large scale density tests were completed and compared to the equivalent Dr of 45.8% for 90% DDR (with 95 % confidence). The results are summarised in Fig. 10. The equivalent Dr from the results of the seven large scale density tests are also shown on Fig. 10.

Note that the field density tests were completed at a different time as the CPTs and settlement may have occurred within the compressible clays beneath the sand platform between tests. As such, the depth of the field density tests was corrected based on the measured settlement from adjacent settlement plates across the New Runway site.

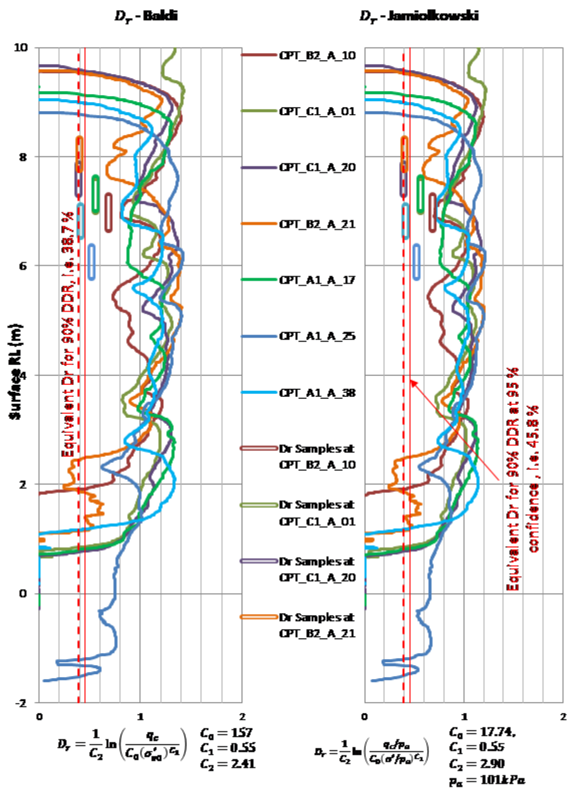

Figure 10. Empirical correlations of Dr to CPT data at Large Scale Insitu Test Locations.

6. Empirical correlations of relative density (Dr) to DMT data

Two empirical correlations of Dr to the horizontal stress index KD from Dilatometer (DMT) test data by Jamiolkowski et al (2001) were used to assess the density of the sand fill. As with the correlations Dr to q_c from CPT data as above, these empirical relationships were determined from Ticino sands.

Empirical correlations of Dr to KD from DMT data by Jamiolkowski et al (2001) use the following relationships in Eq. (4) and Eq. (5):

$$D_R = \frac{1}{C_2} \ln\left(\frac{K_D}{C_0(\sigma'_{v0})^{C_1} p_a^{1-C_1}}\right) \quad (4)$$

, where $C_0 = 0.0053$, $C_1=0.18$, $C_2 = 2.60$, $p_a=101$ kPa (atmospheric pressure).

$$D_R = \frac{1}{B} \ln\frac{K_D}{A} \quad (5)$$

, where A=0.53, B=2.42.

Using each of these relationships, relative density, Dr, was estimated using the DMT data at the ten locations tested and compared to the equivalent Dr of 45.8% for 90% DDR at a 95 % confidence level and Dr of 38.7% for 90% DDR mean value. The results are summarised in Fig. 11.

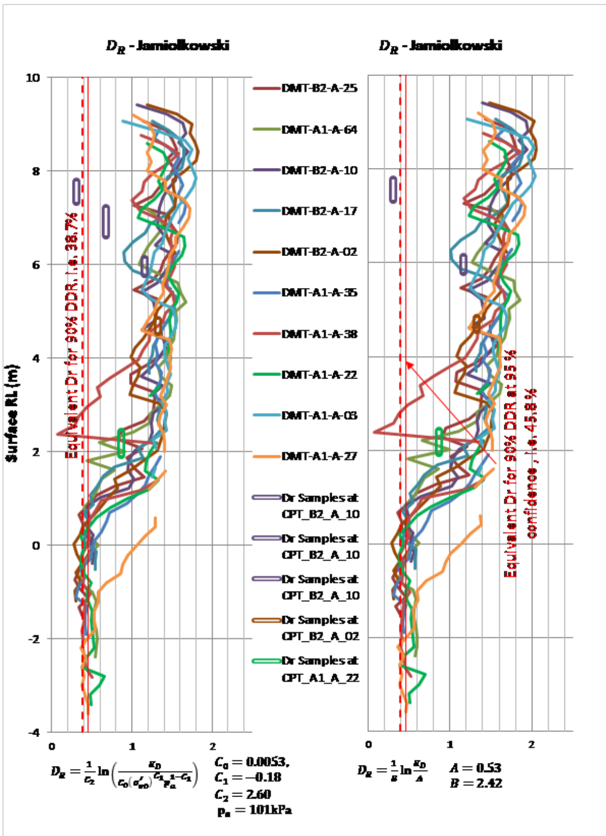

Figure 11. Empirical correlations of Dr to DMT data at ten DMT Locations.

7. *Development of a site-specific correlation of Dr to CPT data*

The results presented in Fig. 10 and Fig. 11 above using the relationships by Baldi et al [1] and Jamiolkowski et al [2], showed a tendency to over-estimate Dr for both CPT and DMT data. The correlations were established based on laboratory testing on sands which were generally coarser than and contained lower proportions of quartz than the sand on the New Runway site and as such a site-specific correlation between Dr and CPT test results was established. Note that no attempt was made to establish a site-specific correlation for dilatomteter test results, since only limited dilatometer testing has been undertaken across the site and can therefore not be used to assess compliance with Specification requirements.

The form of correlation that was adopted is as shown below in Fig. 12 (reproduced from Figure 5.46 in Lunne [5] based on laboratory data from [3]). Note that that data shown in Fig. 12 has a relatively large scatter and illustrates the potential variation in Dr for any given value of normalised q_c. Also, the equation shown in Fig. 12 (which represents the "best fit" correlation to the data shown in the sketch) gives values for Dr that closely match those given by the equations above.

Measured values of Dr for the New Runway site are plotted in Fig. 13, as a function of normalised q_c. This plot presents density results from the following testing:

- large-scale density tests carried out by Golder;
- nuclear gauge density tests, and immediately adjacent sand replacement tests carried out by Golder during sand placement; and
- selected nuclear gauge density tests carried out by the contractor.

It was found that sand replacement tests performed by the contractor (during sand placement) significantly over-estimated the in-situ density compared with their adjacent nuclear gauge density tests. Golder subsequently completed sand replacement and nuclear density tests which indicated a much smaller and consistent variation between the two test methods. The nuclear gauge density tests and sand replacement tests carried out by Golder were conducted between December 2014 and March 2015 at locations adjacent to CPT tests carried out by the contractor. These tests were completed by excavating down from the final reclamation surface level. The tests plotted on Fig. 13 were carried out at depths between 1.2 m and 2.3 m below surface.

A total of 796 records of nuclear gauge density tests completed by the contractor were provided. This testing was carried at between June 2014 and January 2015, during the placement of the reclamation sand. Within this set of data, there are 16 results from locations that are within 5 m of a CPT test (which were carried out later following completion of reclamation). Data from these locations is potentially suitable for establishing a correlation between Dr and normalised q_c and have also been included in Fig. 13.

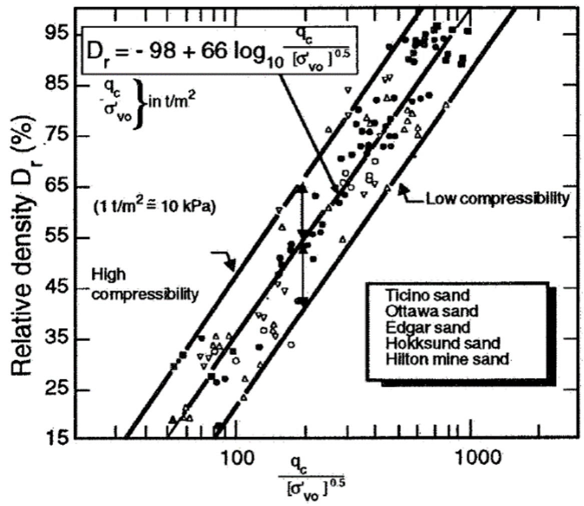

Figure 12. Influence of compressibility on NC, uncemented, unaged, predominantly quartz sands (after Jamiolkowski [3]) showing the scatter in results (from Lunne [5]).

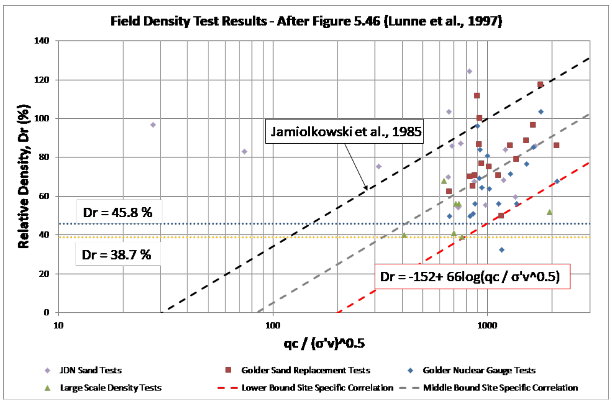

Figure 13. New Runway site specific correlation of relative density with normalized cone tip resistance.

The following relationships are plotted on Fig.13:

- Black dashed line:

$$D_r = -98 + 66\,log\frac{q_c}{[\sigma'_{vo}]^{0.5}} \quad (6)$$

This is the relationship shown on Fig. 12 i.e. the best fit line to the data from Jamiolkowski [3]. Note that this line lies close to the upper bound of the New Runway site data. There is overlap between the Jamiolkowski data and the New Runway site data, however the New Runway site data generally lies below the Jamiolkowski data (i.e. at lower relative densities). It is interpreted that the generally lower values of Dr for the New Runway site are due to differences in particle size distribution and quartz content.

- Grey dashed line:

$$D_r = -127 + 66\log\frac{q_c}{[\sigma'_{vo}]^{0.5}} \quad (7)$$

This line represents the visually assessed line of best fit for the New Runway site data, excluding some outliers from the data set for the contractor nuclear gauge density tests. The line represents the mean or expected value of Dr for any given value of normalized q_c.

- Red dashed line:

$$D_r = -152 + 66\log\frac{q_c}{[\sigma'_{vo}]^{0.5}} \quad (8)$$

This line represents a visually assessed lower bound to the New Runway site data, excluding a few outliers. There is a high degree of confidence that the actual Dr would be higher than that estimated using this equation.

Target 90% DDR values required by the Specification are also plotted:

- Yellow dotted line: Dr = 38.7% i.e. the mean required Dr in order to achieve the Specification requirement of 90%.
- Blue dotted line: Dr = 45.8% i.e. the required Dr to give a 95% confidence level that a 90% DDR has been achieved.

Two approaches were adopted to use the CPT data to assess whether the 90% DDR requirement of the Specification has been met:

1. Option 1 (high level of confidence): Using the red dashed in Fig. 13 (i.e. the lower bound of the data), estimate values of Dr from CPT results, and compare the estimated Dr to the mean required Dr in order to achieve the Specification requirement of 90% (i.e. 38.7%). The majority of the discussion in the following is based on this approach. i.e. results plotting in an envelope from the top left area of the graph and bound by the red dashed line and yellow dotted line (Dr of 38.7 %).
2. Option 2 (lower level of confidence): Using the grey dashed line in Fig. 13 (i.e. the expected/mean value of Dr), estimate values of Dr from CPT results, and compare the estimated Dr to the value required to give a 95% confidence level that a 90% DDR has been achieved (i.e. 45.8%). Results from this approach are described to a lesser extent below.

In the assessment, the upper 300 mm of data was ignored due to loosening of the surface due to wind erosion and other effects as well as 100 mm above the inferred RL of base of sand nominated by the contractor (which is based on available settlement plate data) to account for some uncertainty.

8. Application of the site-specific correlation of Dr to CPT data

The 432 CPT plots provided by the contractor were assessed using the approach presented as Option 1 above. Fig. 14 provides a typical plot of the results. The red shaded areas indicate zones of non-compliance.

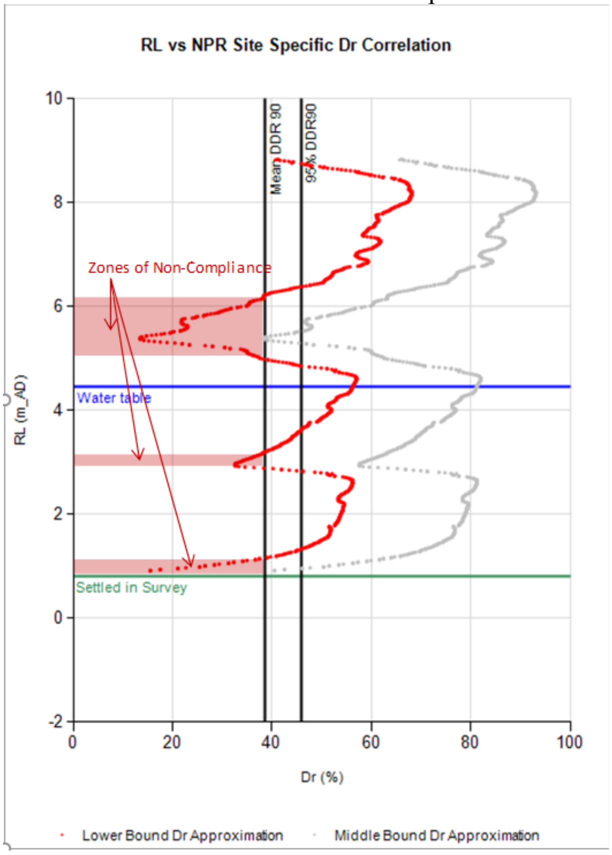

Figure 14. Typical output of CPT data analysed using New Runway site specific Dr correlation against RL (m AD).

The results of all assessed CPTs indicate the following with a high level of confidence:

- 9 CPTs indicate conformance over the full sand profile.
- 77.5% of the all CPT data points (measured at 20 mm intervals) conform to the specification.

Therefore, 423 CPTs indicated some level of non-conformance to the 90% DDR specification requirement based on the conservative approach. This often occurred in isolated zones within the sand profile; with thicknesses as low as that captured by the CPT data recorded interval (i.e. 20 mm) (CPT_G1_B_15), a cumulative average (per CPT) of 1.05 m in thickness, and a maximum cumulative thickness of 5.5 m (CPT_C1_A_25).

Fig. 15 illustrates a histogram plot of the thickness of the non-conforming CPT zones.

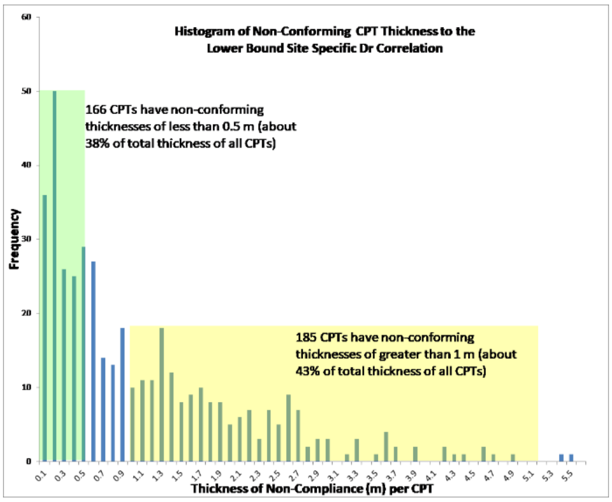

Figure 15. Histogram of non-conforming CPT thickness to lower bound site-specific Dr correlation.

To assess the prevalence and spatial distribution of non-conforming zones, the spatial distribution of locations was plotted with non-conforming values of estimated Dr, for horizontal slices through the site at 0.25 m vertical intervals. The non-conforming CPT were highlighted and colour coded to indicate whether only a small portion of the slice is non-conforming (blue) or whether the full 0.25 m slice is non-conforming (red). If no data is presented, the CPT location was shaded grey. The black CPT locations indicate that the CPT data within this slice conforms to the 90% DDR specification requirement with a high level of confidence. The nuclear gauge sand density testing carried out by the contractor were also included at the relevant slice. Fig. 16 illustrates the slice at RL4.0 m AD (i.e., ranging from RL3.875 m to RL4.125 m AD).

Generally, in areas where the CPTs indicate non-conformance using the approach presented as Option 1, the contractor nuclear gauge tests indicate conformance to the specification.

Figure 16. Example of a slice at RL 4.0 m AD showing non-conforming CPT locations across the New Runway site between RL 3.875 m AD and RL 4.125 m AD.

If a lower level of confidence is adopted (i.e. Option 2 for assessment of the data), the results indicate the following:

- 194 CPTs indicate conformance over the full sand profile.
- 97.2% of the CPT data points (measured at 20 mm intervals) conform to the specification.

Therefore, 238 CPTs indicated some level of non-conformance to the 90% DDR specification requirement based on the lower confidence approach. This often occurred in isolated zones within the sand profile; with thicknesses as low as that captured by the CPT data recorded interval (i.e. 20 mm) (CPT_G2_A_21), a cumulative average (per CPT) of 240 mm in thickness, and a maximum cumulative thickness of 2.1 m (CPT_B2_A_05).

Fig. 17 illustrates a histogram plot of the thickness of the non-conforming CPT zones.

Generally, the contractor nuclear gauge tests correlate well with the CPT assessment using the Option 2 approach.

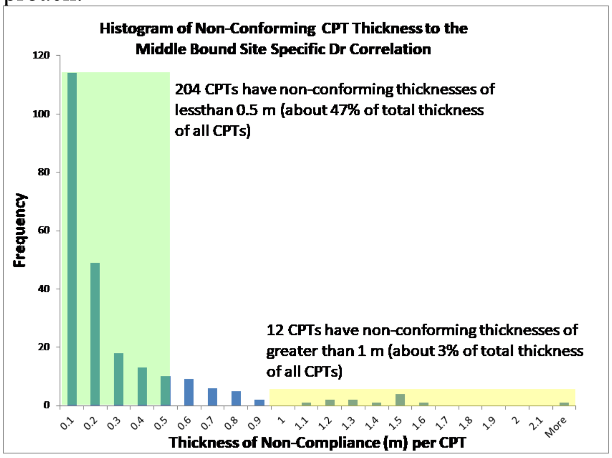

Figure 17. Histogram of non-conforming CPT thickness to middle bound site-specific Dr correlation.

9. Relating results to assess the design impact

The comparison of CPT results and direct measurements of density and density ratio as discussed above indicate that there is a degree of uncertainty involved in estimating dry density ratio from CPT results. Notwithstanding this uncertainty, the results indicate evidence of non-conformance to the specification in places within the New Runway reclamation, in terms of achieving the required dry density ratio.

The comments and information provided in the foregoing summarize the potential extent of zones where required dry density ratio has not been achieved, however it has not addressed the degree to which the dry density ratio may be less than that required. Using the correlation represented by the red line on Fig. 13 (i.e. Option 1 approach), the distribution of dry density ratio estimated from CPT data is illustrated in Fig. 18. Note that dry density ratios in Fig. 18 have been calculated using a maximum dry density of 1.68 t/m^3, and a minimum dry density of 1.39 t/m^3. These represent, respectively, the upper bound of measured maximum dry density, and the lower bound of measured minimum dry density (refer to Relative Density Assessment section above). This combination of upper bound maximum dry density and lower bound minimum dry density gives the lowest values of estimated dry density ratio.

These results indicate that with a high degree of confidence (i.e. using the lower bound correlation between Dr and normalized q_c), only 1% of the reclamation sand has a dry density ratio of less than 85%.

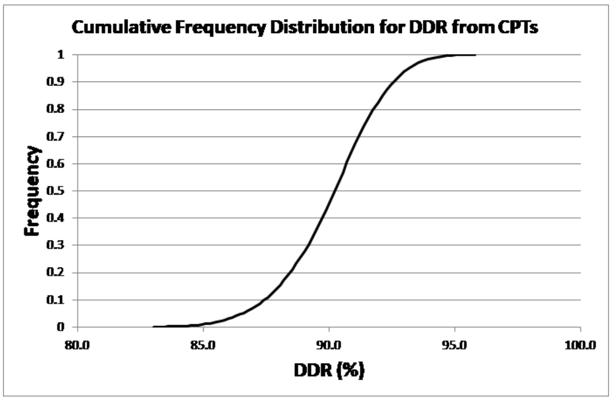

Figure 18. Cumulative frequency distribution for DDR estimated from CPT data.

In terms of consequences to the NPR project, there were two main aspects which were considered by the designers as a result of this assessment:

1. impact on the surcharge effectiveness as a result of zones of lower than target density; and
2. impact on performance of the sand as subgrade to pavements.

The object of the sand surcharge was to provide weight in order to load the underlying compressible soils to facilitate consolidation settlement; the dissipation of pore water over time. Our previous assessments for the project indicated that esimates of post-construction settlement are not sensitive to the assumed density of the sand fill, provided similar densities apply for the sand below final level and the surcharge sand above this level. Hence, it is unlikely that there will be any impact on surcharge performance and post-construction settlement as a result of the zones of potentially non-conformance in relation ot the dry density ratio requirement.

Lower density zones of sand will, in general, have lower stiffness than sand of higher density. However, as part of the pavement construction methodology the sand immediately below the pavement level will be compacted. It is possible that in some locations, sand with low density will be present below the depth of influence of the compaction, but still within the depth of influence of aircraft wheel loadings. The significance of such zones (identified in our assessment above) of low stiffness material will need to be assessed by the pavement designers.

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