

# CASE STUDY: IMPACT OF JET GROUTED COLUMN VARIABILITY ON A BASE BLOCK IN SAND

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## ABSTRACT

To construct an underground rail dump station at a port on a land reclaimed island in Australia, diaphragm walls and a base block designed of overlapping jet grout columns was used, aiming to allow excavation without dewatering. The base block varied between a depth of 8.9 and 19.4 m (surface RL ~6 m AHD) with material mainly consisting of sands. Proximity to the harbour provided a groundwater head boundary, with typical levels of 2 m AHD. Jet grout columns were designed with diameters between 2.1 and 2.7 m and a trial at the site was performed prior to construction. Failure of water tightness tests prior to excavation resulted in a second layer of jet grout columns being installed immediately below the original base block. During excavation of the material within the dump station gaps in the base block led to boiling of the sand, often before the base block level was exposed, preventing further excavation or construction. Ultimately an external dewatering and reinjection system was required to allow further excavation and construction of a concrete base slab on top of the base block. Investigation post construction by PSM highlighted the importance of jet grout column trial interpretation, the influence of column diameter, tilt and position variability and the consequence of small gaps in the base block. Monte Carlo techniques, based on observed as-built column variability, were used to demonstrate the impact of variability on the continuity of the base slab. These indicated that near perfect construction was required if the project objective was to be achieved.

## 1 INTRODUCTION

An underground rail dump station at a port in Australia was constructed in medium dense to dense, medium grained sand below the water table. The site is on a reclaimed land island. The harbour is in close proximity to the site and provides a groundwater head boundary, with typically the groundwater table at 2 m AHD (Australian Height Datum). The construction process aimed to remove the need for external dewatering. To meet this aim a combination of a base block (designed as overlapping jet grout columns) and vertical diaphragm walls were designed to limit inflows and allow excavation down to the top of the base block where a formal concrete base slab would be installed to create a water tight seal. The jet grout column design consisted of 2.1 to 2.7 m diameter columns in an overlapping grid pattern and design column thicknesses between 2.7 and 4.9 m depth. A trial of the jet grout column design parameters was undertaken in an area adjacent to the dump station prior to creating the base block jet grout columns. The dump station was separated out into seven individual 'cells' with the top of the jet grout base slab varying between -0.47 and -8.48 m AHD (refer to Figure 1). The ground surface was typically at 6 m AHD resulting in columns installed below depths from 6.5 to 14.5 m.

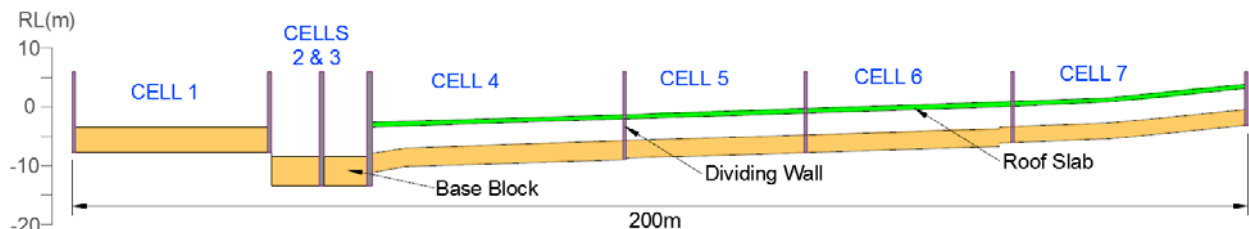


Figure 1: Dump Station layout and cells

## 2 JET GROUTING

Jet grouting is a process where velocity from a high energy jet is used to destroy the soil structure and simultaneously mix cement grout into the in-situ soil. To form a jet grout column the drilling string and the orifice discharging the grout is lifted and rotated. The penetration of the jet grout mixture, and consequentially the diameter of the jet grout column, is a function of the soil and the amount of energy imparted to the surrounding soil by the jet grout. The energy imparted is typically termed the 'specific energy', which can be expressed as a function of the jet grout method (e.g. double nozzle), grout pressure, grout flow and withdraw rate. The specific energy ( $E_s$ ) can be expressed as:

$$E_s = \frac{1}{10^6} \frac{v^2}{2g} \rho_{grout} g \frac{Q}{W} = P_{nozzle} \frac{Q}{W} \quad [MJ/m] \quad (1)$$

Where  $v$  is the velocity at the jet nozzle (m/s),  $\rho_{grout}$  is the density of the grout ( $kg/m^3$ ),  $Q$  is the grout flow ( $m^3/min = 1000 \text{ L/min}$ ),  $W$  is the withdraw rate (m/min) and  $P_{nozzle}$  is the jet pressure at the nozzle (MPa). The withdraw rate is equal to the withdraw step size (m/step) divided by the drill string rotation tempo (min/step). Note the drill string rotation tempo and the specific energy are directly proportional.

The specific energy can be effectively controlled with a jet grouting rig through variation of the grout flow and pump rates as well as the withdraw speed. Other things being equal, the higher the specific energy the larger the column created. Based on the expected soil properties a relationship between the specific energy and the column diameter is required to complete a jet grout design.

## 3 CASE HISTORY

During construction of the jet grout base block a number of adjustments to the construction design were made as a result of probing and water tightness test results. A summary of some of the critical aspects of the construction design are outlined below.

### 3.1 SITE DETAILS

The site consists of Permian aged shale, siltstone, sandstone and conglomerate (typically at depths of 45 to 55 m) which is overlain by Quaternary alluvium and then dredged sand. The alluvium consists of fine grained estuarine sediments and fluvial sands. A series of CPT (Cone Penetrometer Test) investigations were performed at the dump station location prior to construction. At the depths of the proposed base block the material was classified as medium dense to dense, medium grained sand with some clayey sand and gravelly sand layers. A cone tip resistance less than 30 MPa was typically encountered at these depths. The estimated permeability of the layer, from pumping tests and particle size distribution, was  $2.5 \times 10^{-4}$  m/s.

During site investigations the groundwater table was measured to be between 1.8 and 3.35 m depth (i.e. 2.1 to 3.62 m AHD). A design groundwater table level of 2 m AHD was adopted.

### 3.2 BASE BLOCK DESIGN

The base block was designed as a system of overlapping jet grout columns. Jet grout columns were sequenced and installed as a set of primary, secondary and tertiary columns (see Figure 2).

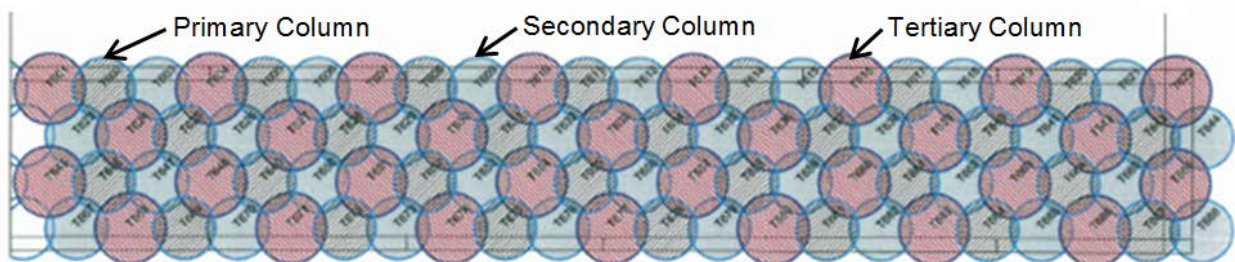


Figure 2: Typical design jet grout column sequence and layout

The tertiary columns are the final columns in the sequence and some additional design allowances were made to improve performance. These included setting the base of the tertiary columns an additional 300 mm lower than the primary and secondary columns as well as at mid depth of the tertiary column the tempo was increased by 50% (which also increases the specific energy by 50%) for a 300 mm long section. Both of these aspects were included to improve grout ‘connection’ between the adjacent columns. Additionally any columns adjacent to the diaphragm wall also included a 300 mm long section with 50% increased tempo.

The layout of the columns was established to achieve a 300 mm overlap between primary and secondary columns and a 600 mm overlap between primary/secondary and tertiary columns. For design drill string tilt deviations of 0.5% were assumed. For a maximum drilling depth of 19.4 m (for the original base block) this would give a maximum deviation of 97 mm.

As can be seen in Figure 1 the construction of the dump station was split into a number of ‘cells’, which was implemented via separating ‘walls’ of 1.2 m diameter jet grout columns installed from the surface level. The base level of each cell varied, as did jet grout base plug thicknesses. This resulted in a minimum base block thickness of 2.4 m (in Cell 7) and a maximum thickness of 4.9 m in Cells 2 and 3. The base block varied between depths of -0.47 m AHD (i.e. top of the Cell 7 base block) and -13.4 m AHD (i.e. base of Cells 2 and 3 base block). Giving total drill depths between 8.9 and 19.4 m.

Column diameters were designed as 2.2 m for primary columns, 2.1 – 2.2 m for secondary columns and 2.5 m for tertiary columns. The design of the jet grout columns was modified over the course of the construction of the base block. Based on a double jet with a 5.5 mm diameter nozzle and water pre-cutting jet grout set up Table 1 presents the typical design parameters. Figure 7 shows the design points for the design presented in Table 1.

**Table 1: Jet grout column design**

Column Diameter (m)	Nozzle Pressure (bar)	Grout Flow Rate (L/min)	Withdraw Speed (cm/min)	Specific Energy (MJ/m)
1.2	326	320	25.7	40.6
2.1	335	320	9.5 – 10	107 – 113
2.2	326 – 341	320	7.5 – 10	104 – 145
2.5	326 – 341	320	5.5 – 6.2	172 – 198
2.7	341	320	4.5	242.5

### 3.3 WATER TIGHTNESS TESTING

A water tightness test was specified for the cells upon completion of the diaphragm walls and base block. An ‘acceptable leakage’ rate was defined as between 360 and 500 L/hr when the water level inside the cell was drawn down to -1 m AHD (i.e. a drawdown of approximately 3 m from the design groundwater table). This was typically assessed using a pumping test with one or two pumping wells and generally two monitoring wells per cell for a multi-day pumping period. It is important to understand that passing this water tightness test does not necessarily mean that excavation to the top of the base block can be achieved without external dewatering (for example sand boiling in ‘un-grouted’ sections of the base block leading to excessive inflows). As an indication, for Cell 7 (which has the shallowest base block), assuming a grout permeability of  $1.7 \times 10^{-7}$  m/s, the water tightness test could be passed even with an approximately 650 mm diameter un-grouted ‘hole’ in the base block.

Following completion of the base block construction all seven cells failed the water tightness test. To investigate the condition of the base block core recovery drilling, probe drilling (to see if resistance is met at the top of the base block), CPT’s and a review of installation records to check all columns were installed in the correct position was undertaken across the cells. Probe drilling was the most common investigation technique used and multiple instances of ‘patchy’ or little resistance being met at the level of the base block were recorded. As a result a series of targeted remedial columns were installed in the identified issue areas in the base block, typically resulting in a significant reduction in inflow rate under the water tightness test. However, only one cell passed the water tightness test (cell 2, which is has one of the deepest base blocks).

### 3.4 SECOND BASE BLOCK

Following non-compliance with the water tightness testing a second layer of jet grout columns was installed below the original jet grout base block in Cells 1 to 4 (i.e. the cells with the deepest base block levels) to further remediate the jet

grout base block. The jet grout rig drilled through the original base block in order to install the second base block. The base block was designed as a 1 m thick layer consisting of generally 2.5 and 2.7 m diameter jet grout columns with a typical 400 mm overlap. Table 1 presents the jet grout column design parameters. The combined dual base block passed the specified water tightness tests in cells 1 and 3.

### 3.5 CONSEQUENCE OF INFLOWS THROUGH THE BASE BLOCK

Following installation of the second base block the jet grout works were considered completed and excavation of the material within the cells began. As planned this was conducted without use of external dewatering. If there was no sand boiling/piping, assuming cell 7 had passed the water tightness test, expected inflows for a fully excavated cell 7 would be in the order of 0.2 L/s. During excavation two major leak/inflow occurred as a result of sand boiling and piping through ‘gaps’ in the base block events (which increased the ‘gap permeability’, with estimated inflows in excess of 20 L/s), ultimately leading to significant delays and a change to an external dewatering and reinjection system to allow further excavation.

The first leak event occurred in Cell 7 (i.e. the shallowest base block level and consequentially the lowest external groundwater head). Excavation to the top of the base block was achieved in at least part of Cell 7. Inflows in the order of 22L/s occurred with a 300 mm diameter hole in the base block identified as one of the sources of the inflow.

The second leak event occurred in cells 2 and 3 (which have the deepest base block level, largest external groundwater head and a second base block installed). The leak occurred prior to the excavation exposing the base block level with somewhere between 0.5 and 1.5 m of sand still overlying the top of the base block. A pump system was set up and an equilibrium water level was achieved with an average pump rate of 18 to 22 L/s (for an approximately 5.5 m groundwater head difference).

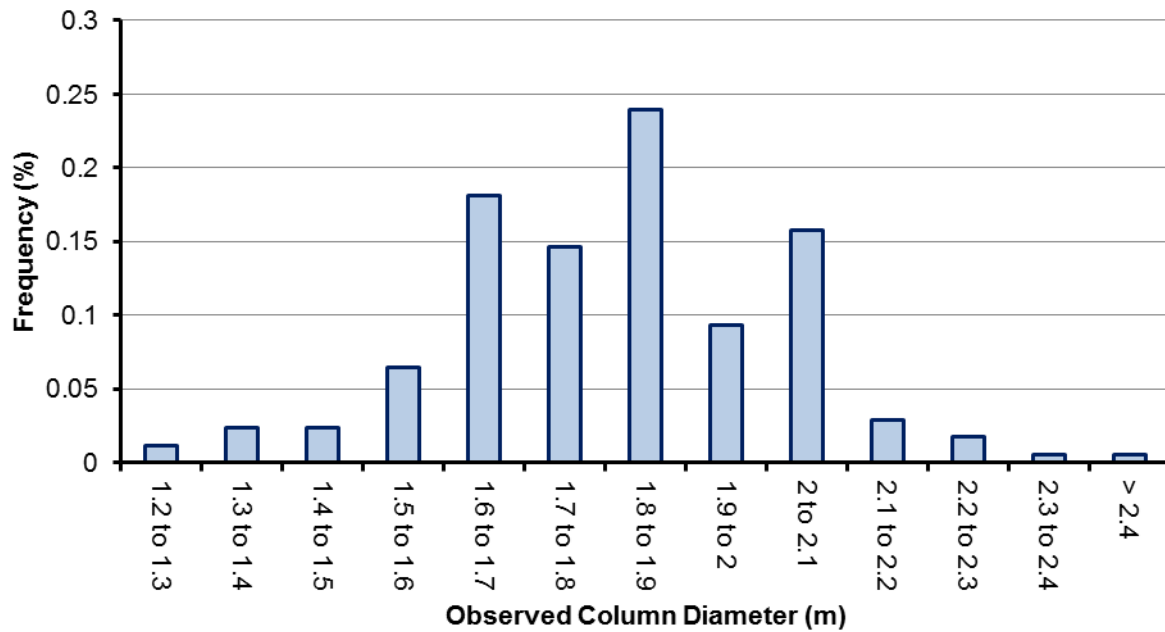
Under low groundwater heads the inflow through modest gaps in a base block may be able to be managed. For example a pipe can be installed in the gap, then grout applied around the pipe (whilst water flows through the pipe) and finally grouting the inside of the pipe to form a seal. However, the state change of boiling and piping sand in this project, along with site water discharge restrictions, rendered such remediation options unachievable.

## 4 AS BUILT BASE BLOCK CONDITION

With an external dewatering and reinjection system in operation excavation to the top of the jet grout base block was achieved, at which time survey and probing for gaps in the jet grout base block was undertaken prior to installation of the base slab. The observations and measurements made of the base block along with the jet grout design and monitoring allowed assessment of the construction and whether the observed consequence could have been foreseen.

### 4.1 COLUMN DIAMETER

A total of 190 measurements of the constructed base block jet grout column were made via a combination of survey and tape measurement. Analysis of the as built column diameters has shown that the variation in the column diameter for the same specific energy can be represented by a normal distribution with a standard deviation of 0.23 m and a coefficient of variation of 0.13 (see Figure 3). The mean diameter was found to be approximately 13% smaller than the design diameter. A normal distribution for variation in column diameter from the mean is consistent with recommendations from Croce *et al.* (2014). Additionally Croce *et al.* (2014) recommends that in cases without site specific data coefficient of variations between 0.05 and 0.1 for medium soil heterogeneity and 0.05 and 0.20 for high soil heterogeneity can be expected. Pre-construction CPT results have shown variability in cone tip resistance between 10 and 15 MPa over short distances, as such medium to high soil heterogeneity does not seem unreasonable.



**Figure 3: Histogram of jet grout columns with design diameters of 2.2 m (from 171 measurements)**

#### 4.2 COLUMN TILT AND POSITION

Deviation in the as built column position can be as a result of a set-out error at the surface and/or drill string tilt. Survey of the as built base block and surface set-out points for the jet grout columns allowed the as built position variation to be established. Differences between the installed and design positions at the surface was found to be an average of 14.9 mm from 174 measurements. This offset is considered insignificant to account for on its own (i.e. separately to tilt) and is sub-sequentially incorporated into overall tilt measurements. The overall tilt (i.e. surface offset and drilling tilt combined) from 239 as built column positions was found to fit a normal distribution with a mean of 0.0104 m/m and a standard deviation of 0.0082 m/m. The azimuth of this tilt was found to be random and consistent with a uniform probability distribution. A normal distribution for tilt variation and a uniform distribution for tilt azimuth is consistent with recommendations from Croce *et al.* (2014).

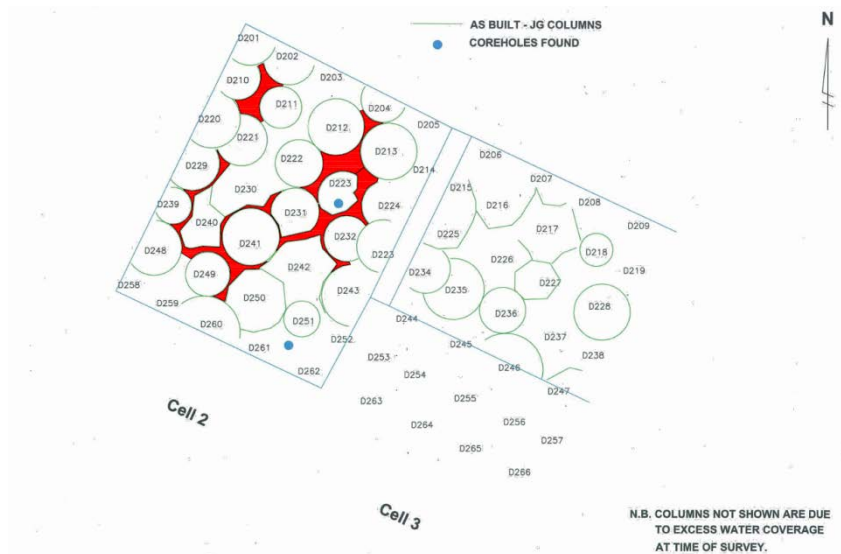
The as built mean overall tilt is approximately 1%. This is double the 0.5% assumed in the design. Croce *et al.* (2014) suggests that deviations between 0.3% and 1% are reasonable first pass design tilt estimates in the absence of site specific data, examples are also provided with tilt standard deviations in the order of 0.005 m/m.

#### 4.3 COLUMN PATTERN

In the surface of the base block a number instances where adjacent jet grout columns did not appear to overlap were observed. Figure 4 shows a photograph of the as built base block surface, the red highlighted area is an example of an area where columns appears to have not overlapped fully. Figure 5 shows the results of survey of the top of the base block for cells 2 and 3, areas where adjacent columns do not overlap have been highlighted in red. Figures 4 and 5 provide examples of the magnitude of ‘gaps’ that were observed to have occurred in the surface of the base block.



**Figure 4: Example of top surface of base block (red indicates columns not overlapping)**

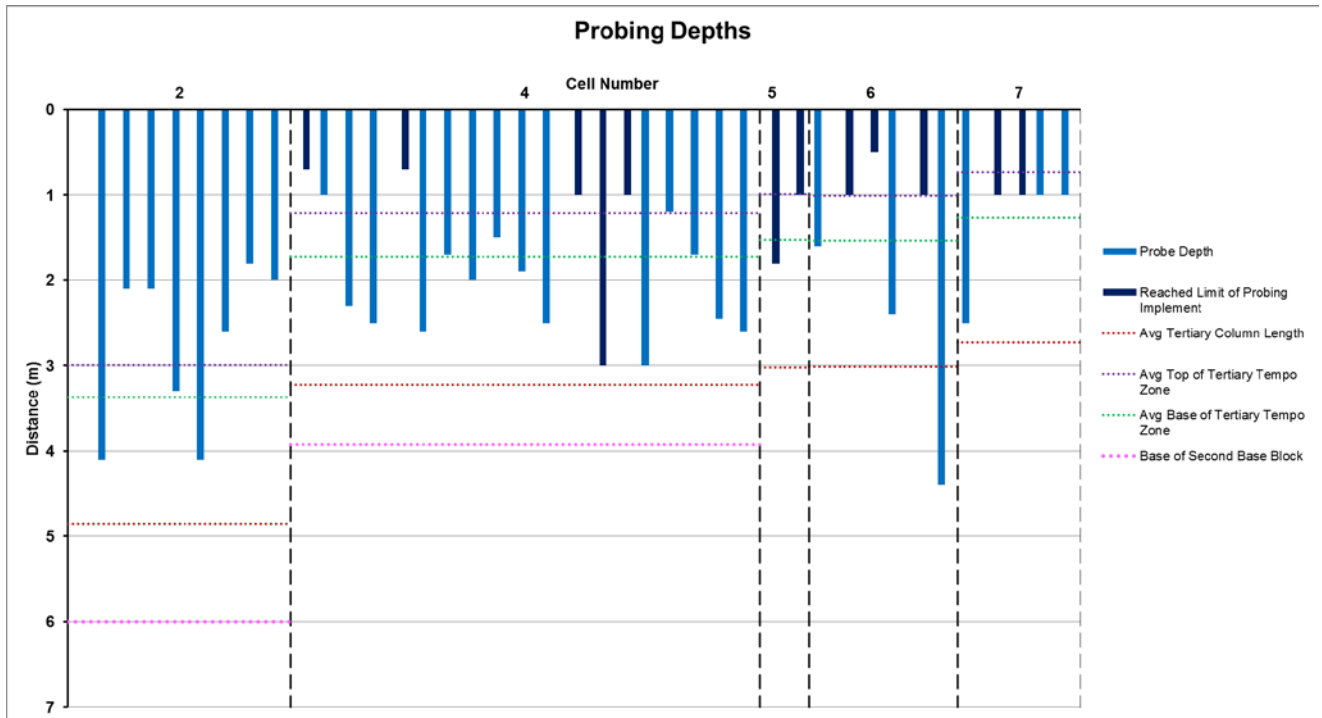


**Figure 5: Cells 2 and 3 survey of base block top surface (red indicates columns not overlapping)**

#### 4.4 GAP PENETRATION

After the base block had been installed, probing of gaps in the base block was undertaken. Probing was undertaken with a number of different instruments including a wooden staff, star picket, 10 mm steel bar and a hose. The depth of penetration was recorded for each of the 40 locations probed. To assess the as built thickness of the base block and the position of the ‘increased tempo’ section in the tertiary columns a random selection of 10 to 15 construction records from each cell were summarised. Figure 6 shows the summarised as built depths for the original and second base block along with the records of the probing.

Figure 6 shows that it was often possible to probe from the top of the base block to below the level of the increased tempo section (for tertiary columns) and in one instance the probe penetrated through the entire thickness of the base block. As most of the probing instruments were quite rigid being unable to penetrate all the way to the base of the base block does not necessarily mean there was not a flow path through the entire base block at that location.



**Figure 6: Summary of probing through jet grout base block**

## 5 MODELLING VARIABILITY

Given that it was not possible to measure the exact condition of jet grout columns prior to excavation of the overlying material, a stochastic approach was used to display the likelihood of gaps in base block using the design jet grout column parameters as well as back-analysed parameters from the as-built data once variables such as diameter variation and drill string tilt were accounted for. This was used to answer following questions:

- If the mean column diameter was as per the design assumptions, how likely was it that adjacent columns would not overlap?
- With the benefit of only the jet grout trial results, could the under sizing of the columns been predicted?
- With the benefit of the as built data, how likely was the observed base block condition?
- What was the likely as built condition of the second base block (which could not be observed)?

### 5.1 MONTE CARLO TECHNIQUE

A Monte Carlo technique, applied through a customised Matlab code, was used to stochastically vary the deviation from the mean diameter, the tilt azimuth and tilt inclination. The design column layout (applied at the ground surface), column depths and specific energy are used as deterministic inputs. A relationship between the design specific energy and column diameter was used to model the mean typical column diameter. Figure 7 presents the jet grout design values (as per Table 1), a 'design line' which fits these points, the 190 measurements of as built column diameter and an 'assessed fit line' which fits the as built data. To establish the stochastic column diameter for a particular column the design specific energy is used to determine the typical mean design diameter (i.e. from the design curves shown in Figure 7), a stochastic normal Z score is sampled from a standard normal distribution and the resulting diameter determined using a 0.23 m standard deviation. For columns with an increased tempo zone the same Z score is used but the mean diameter is re-calculated for the increased specific energy. Tilts are directly sampled from a normal distribution with a mean of 0.0104 m/m and a standard deviation of 0.0082 m/m (N.B. sampled tilts were limited to two standard deviations from the mean as it is assumed that larger deviations would be noted and remediated in construction). Tilt azimuth is directly sampled from a standard uniform distribution with values between 0° and 360°. Figure 8 shows a sketch of how the position of a stochastically generated column is established from the inputs (noting that the surface offset is incorporated into the overall tilt).

It is important to note that the modelled values of column diameter standard deviation and drill tilt mean and standard deviation are within typical bounds available in literature (refer to Section 4).

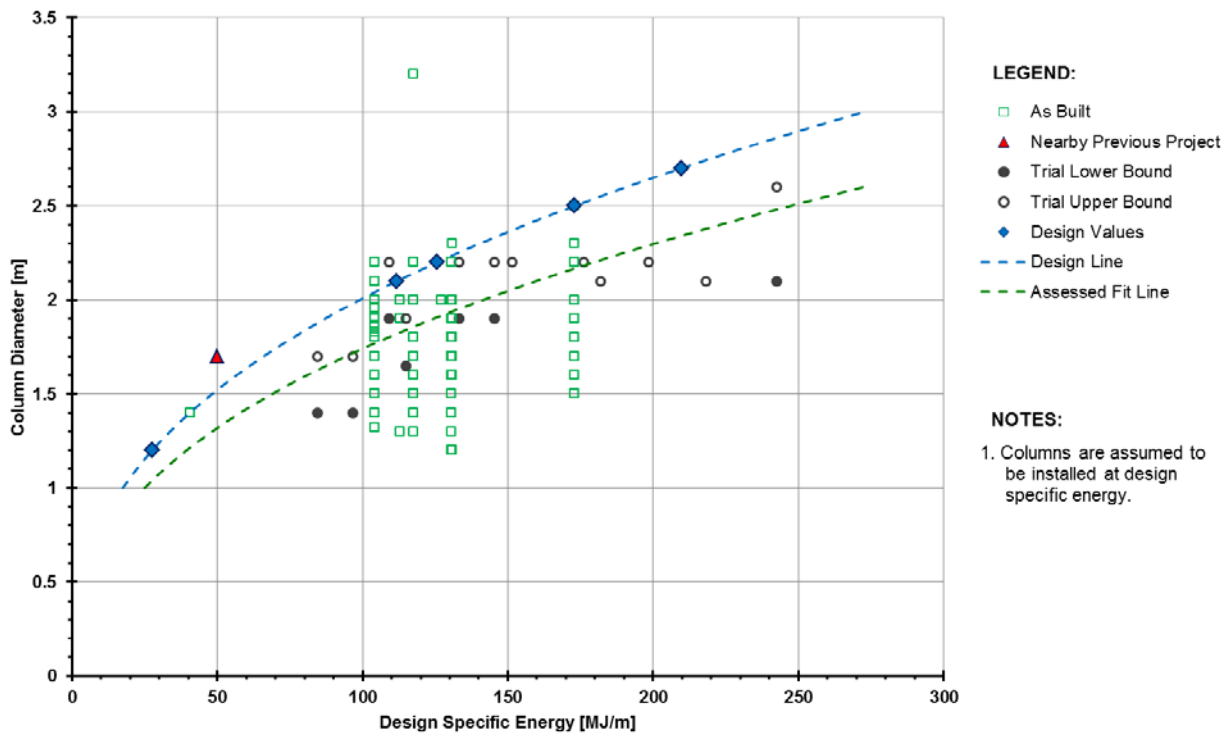


Figure 7: Jet grout column specific energy and diameter relationships

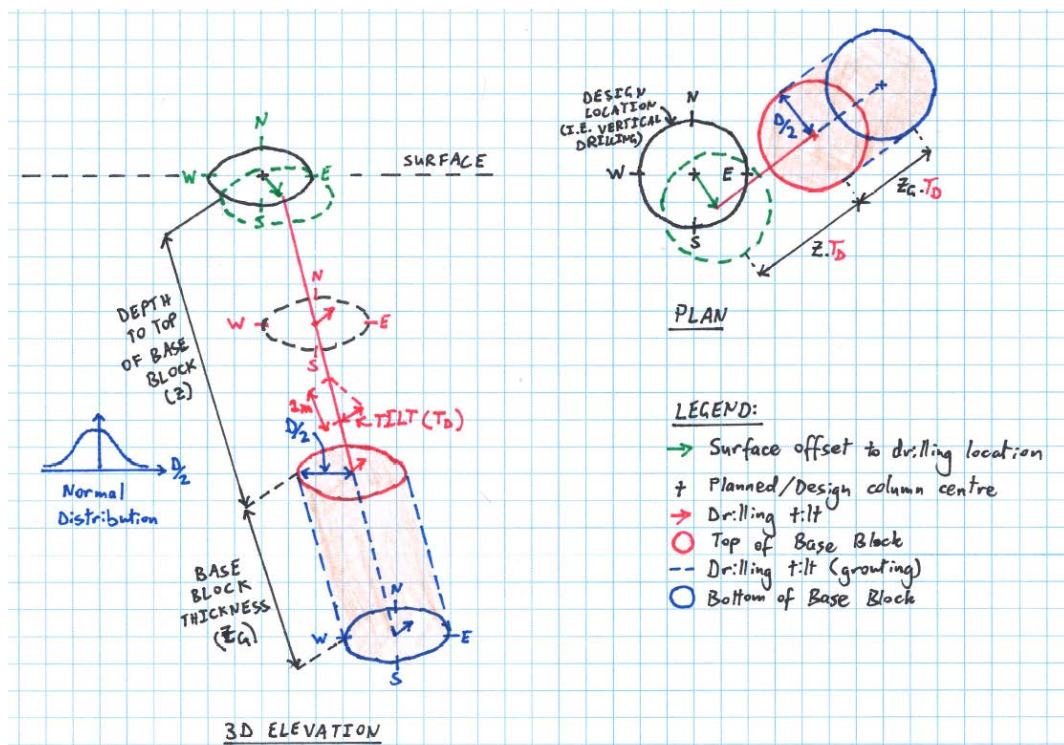


Figure 8: Sketch of grout column location variability

Prior to construction of the original base block a jet grout column trial was conducted adjacent to the dump station area. The trial columns were installed over a 3 m length between depths of -4 and -7 m AHD (i.e. 10 to 13 m depth, which is representative of the design base block level). CPTs and core drilling were used to assess the trial column positions. Neither method is a direct measure of the installed column diameter, but can give an indication of minimum achieved diameters (when jet grout is intersected) or upper bounds for column diameters (when jet grout is not intersected). Figure 7 presents bounds for the trial column diameters as interpreted by the author post construction of the full base block. As can be seen from Figure 7 achieving the ‘design line’ was unrealistic from the jet grout column trial results (with the design line typically plotting above the upper bound levels from the trial) and that the trial results do not appear inconsistent with the ‘assessed fit line’.

## 5.2 MODEL RESULTS AND DISCUSSION FOR ORIGINAL BASE BLOCK

To assess the impact of variability of different situations the following cases have been modelled:

- Tilt variation only,
- Diameter variation only, and
- Tilt and diameter variation.

For each of the above cases the pattern of jet grout columns at the top of the base block as well as at the level of the increased tempo zone is considered for both the ‘design line’ and the ‘assessed fit line’ from Figure 7. An example of Cells 2 and 3 is presented here. Average results are based on 100 individual Monte Carlo simulations. Table 2 presents a summary of results for the different cases in terms of an average percentage of ‘gaps’ in the overall Cell 2 and 3 base block plan area.

**Table 2: Cells 2 and 3 average percentage of gaps simulation results (%)**

Simulation	Design line		Assessed fit line	
	At Top of Base Block	At Level of Increased Tempo Zone	At Top of Base Block	At Level of Increased Tempo Zone
No variation	0.00	0.00	1.15	0.14
Tilt variation only	0.18	0.03	3.76	1.19
Diameter variation only	0.05	0.002	2.64	0.61
Tilt and diameter variation	0.44	0.08	4.82	1.66

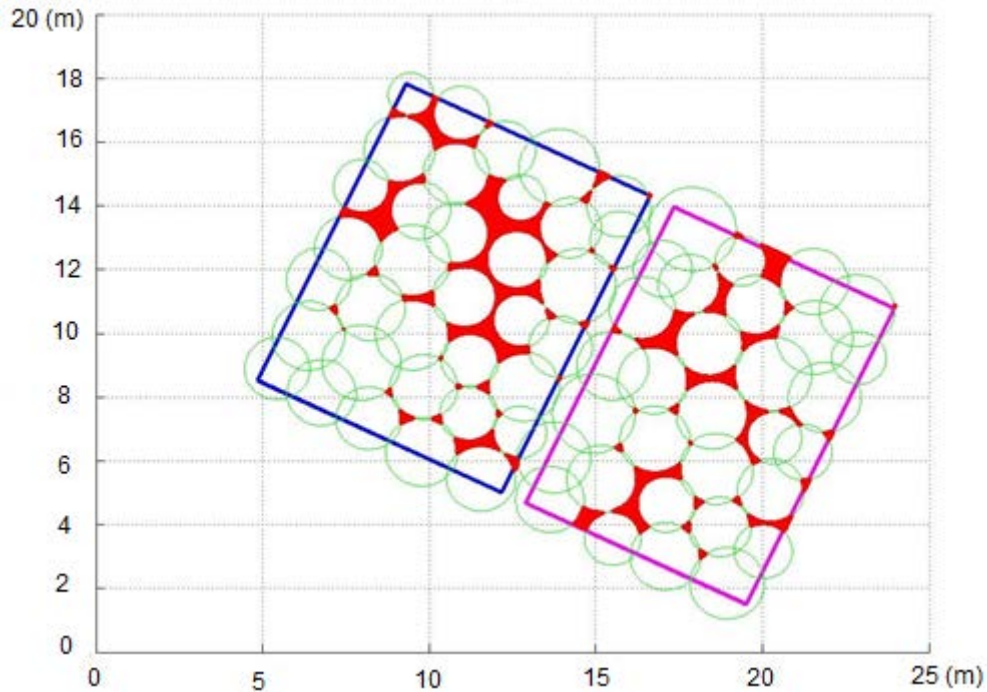
As from Table 2, unsurprisingly given the depth of the base block for Cells 2 and 3, the tilt variation dominates the modelled area of gaps.

Given that the modelled column diameter standard deviation and the mean and standard deviation drill string tilt are within typical bounds available in literature the results are considered applicable to assess the likely result if the mean column diameters were constructed to design. Out of 100 simulations for the ‘design line’ where tilt and diameter variation were modelled only 5 simulations resulted in no gaps for the increased tempo section. Consequentially, even if mean column diameters were to design, gaps (and likely flow paths through the base block) were highly likely. Given the high external groundwater heads even relatively minor flow paths could be expected to result in sand boiling and large inflows. In this respect the state of the art paper by Bourke (2012) states “*Creating a bottom seal (for groundwater control) requires perfection. This is particularly so under high head (>10 psi) [~70 kPa] conditions. A small window (imperfection) can yield significant inflows... enough to create a piping condition and ground losses that exacerbate the problem.*”

Figure 7 shows the interpreted results of the jet grout trial. From these results it is considered possible that a specific energy to column diameter relationship similar to the ‘assessed fit line’ could have been assessed. As such it is considered possible to model a situation consistent with the ‘assessed fit line’ Monte Carlo model without the benefit of the as built data from only the trial results and column diameter standard deviation and drill string tilt mean and standard deviation from literature sources.

The ‘assessed fit line’ Monte Carlo results allow assessment of how likely the observed base block condition is. Out of 100 simulations for the ‘assessed fit line’ where tilt and diameter variation were modelled all simulations resulted in

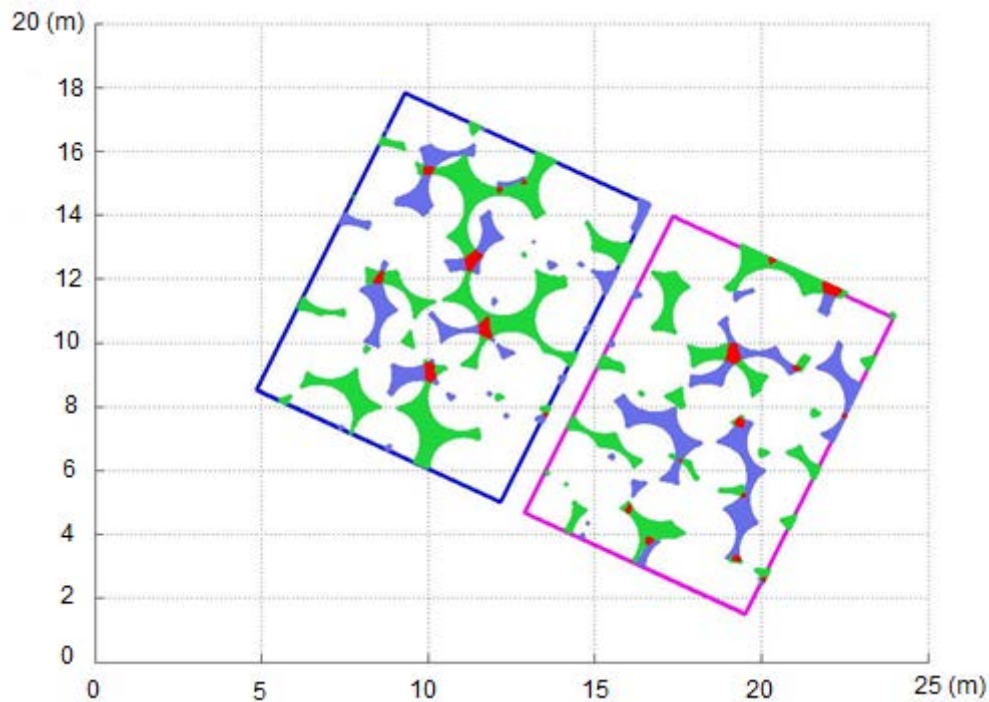
gaps for the increased tempo section. As such the observed condition of gaps in the base block (and the associated consequence of large inflows) was almost certain. Figure 9 shows a simulation result for the ‘assessed fit line’ with tilt and diameter variation that provides 5.6% gaps (i.e. above the Monte Carlo average). The magnitude of gaps shown in Figure 9 is consistent with observations of the constructed base block (see Figures 4 and 5).



**Figure 9: Realisation of top of base block for ‘assessed fit line’ (red indicates simulated gaps)**

### 5.5 IMPROVEMENT FROM SECOND BASE BLOCK

Cells 2 and 3 had a second base block constructed prior to excavation. It was not possible to observe the as built condition of the second base block during construction. In order to investigate the relative improvement from the second base block Monte Carlo techniques were also employed. To assess this, stochastic column positions at the base of the original base block were simulated along with stochastic column positions at the top of the underlying second base block. Comparison between these two sets of columns allowed the ‘interface’ of the original and second base block to be modelled. As tilt variation dominates the resulting gaps only tilt variation has been modelled. From 20 simulations of gaps at the interface it was found that there were an average of 0.01% gaps for the ‘design line’ and an average of 0.42% gaps for the ‘assessed fit line’. Figure 10 shows a simulation of the interface gaps for the ‘assessed fit line’ where blue indicates a simulated gap at the base of the original base block, green indicates a simulated gap at the top of the second base block and red the overlaps between these two layers (i.e. gaps at the interface). The area of ‘overlapping’ gaps at the interface indicates generally an over 50% improvement with the second base block in place when compared with the tilt variation only results from Table 2. However it is likely that inflows would not be limited to the direct connections between the two base blocks. Rather, the gaps in the second base block would provide general access to the base of the original base block and then inflow could progress to adjoining gaps in the original base block that do not directly overlie gaps in the second base block.



**Figure 10: Realisation of original and second base block interface for the ‘assessed fit line’**

## 6 CONCLUSION

Variability in a jet grout column construction process is a well-established and likely phenomenon, in particular for column diameter and the drill string tilt. For the port dump station using jet grout columns to form a groundwater barrier base block in sand with external groundwater heads between 4.9 and 15.4 m it was observed that relatively minor ‘gaps’ led to boiling and piping of the ‘un-grouted’ sand in-between the columns, causing significant inflows and rendering the base block unable to meet its intended purpose. Given the depth of the base block, variability of drill string tilt was the dominant cause of gaps in the base block. This was further exacerbated by the production of generally undersized columns. Despite a jet grout trial, significant probe drilling during construction of the original base block and the installation of a second base block it appears the general under sizing of the columns was not established during construction. Even if columns were constructed to the design mean column diameter the consequence of gaps in the original base block (which could result in boiling and piping) were very likely as a result of a mean 1% drill string tilt and a 0.23 m standard deviation in column diameter. This implies that near perfect construction would have been required to achieve the design aim of excavating to the top of the base block without external dewatering. The construction of a second base block reduced the potential area of gaps at the original and second base block interface. If the original and second base block mean column diameters had conformed to the design line the second base block would likely have made the observed consequence of sand piping much less likely, however the generally undersized columns made the benefit of the second base block much less effective. When constructing a jet grout barrier in sand under groundwater heads able to induce boiling (say in excess of 5 m) careful interpretation of jet grout trials as well as accounting for stochastic drill string tilt and column diameter variation in the design (for example through Monte Carlo methods) is highly recommended to mitigate the potential for gaps in the base block leading to boiling, piping and high inflows.

## 7 REFERENCES

- Croce, P., Flora, A. and Modoni, G. (2014). *Jet Grouting – Technology, Design and Control*. Boca Raton, FL, CRC Press.
- Burke, G.K. (2012). *The State of the Practice of Jet Grouting*. Grouting and Deep Mixing 2012, pp. 74 – 87.