The paper was published in the proceedings of the 12th Australia New Zealand Conference on Geomechanics and was edited by Graham Ramsey. The conference was held in Wellington, New Zealand, 22-25 February 2015.

Assessing probability of not achieving column overlap in jet grout floors and walls

S Amatya[1], M. AGS, C M Haberfield[1], FIEAust and R Zhang[1], MIEAust

[1] Golder Associates Pty Ltd, 570 – 588 Swan Street, Richmond, Victoria, P.O. Box 6079, Hawthorn West, VIC 3122, Australia; PH +61 3 8862 3500; FAX +61 3 8862 3501; email: samatya@golder.com.au

ABSTRACT

Jet grouting technology can be used to provide an effective cut-off to groundwater inflow through the base of an excavation. However the effectiveness of the cut-off relies on sufficient overlap of the jet grout columns, which in turn is impacted by construction tolerances with respect to column diameter, verticality and out-of-position. Even a small lack-of-overlap can render the cut-off ineffective, which can add significant cost and time to construction if not effectively repaired. This paper presents a spreadsheet method for calculating the probability of not achieving overlap between columns. The application of the method is demonstrated for some assumed jet grout column layout and a range of construction tolerances. The paper will be of assistance to designers of jet grout floors.

Keywords: jet grout columns overlap, non-overlap probability, construction tolerances

1 BACKGROUND

Jet grouting, amongst other applications, provides a practical method of achieving a groundwater cut-off for excavations below the water table in permeable ground. For example, it can be used to construct a relatively impermeable floor to a basement excavation and provide a method of sealing between closely spaced piles in retention systems.

Jet grouting is undertaken by drilling a relatively small diameter hole vertically into the ground using a specially designed drilling tool (called a monitor). Once at the desired depth grout, or water and air are ejected under high pressure from nozzles in the monitor. The high pressure jet erodes the soil which is mixed with the injected circle of grout with the monitor at the centre of the circle. As the monitor is slowly raised, a cylinder of jet grout is formed in the ground.

The diameter of the jet grout column usually varies over the length of the column due to natural variations in soil properties. For example in sand, localised reductions in sand grain size, increase in sand density, increase in silt or clay content or presence of cementation can all cause a localised reduction in column diameter. For this reason, the design of columns (in sand for example) is usually based on a prudent assessment of soil grain size and density.

A jet grout floor seal or plug is formed by an aggregation of overlapping, vertical, (nominal) cylindrically shaped, jet grout columns of nominated diameter/s. Columns are generally installed on a regular grid pattern, e.g. a triangular grid, with the centre of each column located at the apexes of each triangle (for example). The order of installation of columns is important so that “shadowing” doesn’t occur. Shadowing occurs when the full cross-section of a jet grout column cannot be formed because of the presence of (say) a hardened, previously installed column or other obstruction (e.g. a CFA pile) which blocks the path of the jet of grout from the monitor and leaves a shadow area of untreated soil .

A jet grout plug design requires selection of a practically achievable column diameter(s) along with selection of column layout and installation sequence so that sufficient column overlap occurs to eliminate any areas of untreated ground and hence limit groundwater inflow to a specified rate. The assessment of sufficient column overlap depends on the potential positional and out-of-verticality tolerances of the jet grouting equipment and potential variation in jet grout column diameter.

It would appear that a common approach to the layout design of jet grout columns for floors and wall seals is to assume that jet grout columns and other foundation components (e.g. piles in a contiguous pile wall or foundation piles) will be installed at their design location. Some allowance is made for construction tolerances, but this appears to be based on a qualitative rather than quantitative assessment. As a result, the layout design may not sufficiently account for construction tolerances and result in areas of untreated ground and hence leakage of groundwater into the excavation. Such leakage, if sufficiently high, can lead to piping and endanger the integrity of the structure.

This paper presents a spreadsheet method which designers can use to estimate the probability of not achieving column overlap when variations in the column verticality and out-of-position are taken into consideration.

Theoretical aspects of conditions required for overlap of two (e.g. seals between piles in a contiguous pile wall) or three circles (e.g. jet grout floor) are presented for the calculation of probability of not achieving overlap. A Monte Carlo simulation method is used to account for variations in position and inclination of columns which are within normal construction tolerances of jet grout installation and the outcomes summed to obtain a probability of not achieving the required overlap. The analysis does not consider variations in column diameter.

2 REQUIREMENT FOR OVERLAP

The necessary theoretical conditions required to achieve overlap for over-lapping jet grout columns is presented below. Two cases are considered – the first relates to sealing the floor of an excavation and the second to sealing the gap between near-contiguous piles in the walls of an excavation. For a jet grout floor, an effective cut-off requires at least three columns to have a common area of overlap, whereas, an effective cut-off can be attained by at least two columns overlapping for the wall. The conditions of a common area of overlap between jet grout columns, with respect to the column layout geometry in particular, are presented herein. These form the basis for the calculation of probability of not achieving overlap.

2.1 Floor

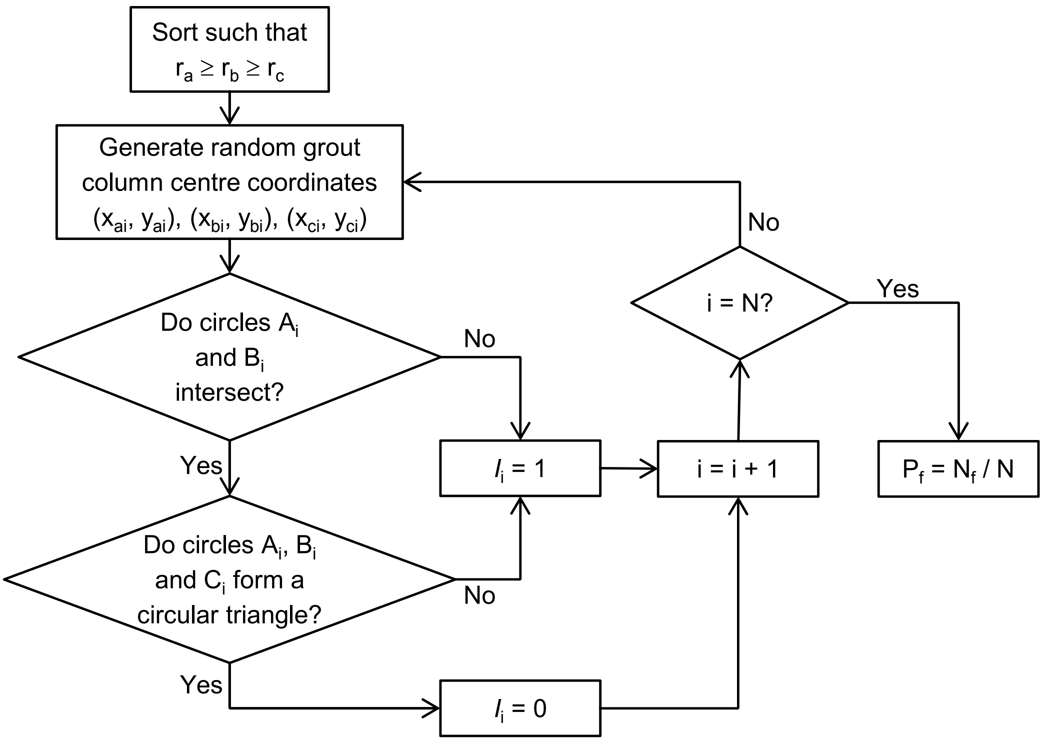
For an effective groundwater cut-off, at least three adjoining columns arranged in an assumed triangular layout should have a common area of overlap. Figure 1 presents equations for overlap for an assumed arrangement of three columns has a common area of overlap. For three circles A, B and C named in decreasing column diameter dimensions, equations F1 and F3 (Figure 1) must be satisfied to guarantee overlap.

2.2 Wall

For an effective cut-off wall, it is essential that any two adjacent columns have sufficient overlap. If a wall layout comprises three columns A, B and C such that overlaps between columns A and C as well as between columns B and C confirm an effective cut-off, a check using Equation F1 (Figure 1) is sufficient. If a small minimum overlap is to be ensured at all times, Equation F1 can be modified as follows, say, for a check of overlap between columns A and C:

$$r_a - r_c + \varepsilon < d_{ac(i)} < r_a + r_c + \varepsilon \qquad (1)$$

where, ε = the minimum distance that defines overlap between columns. In theory this could be 0 m, implying that the columns just touch each other, but practically, some overlap (e.g. 50 mm) is required to ensure good contact between columns.



For three circles A, B and C of radii r_a, r_b and r_c, respectively, and centre-to-centre distance from A to B equal to d_{ab}, from B to C equal to d_{bc} and from C to A equal to d_{ca}, the following equations (after Fewell 2006) are applicable for an i^{th} sampling:

- Circles A_i and B_i intersect if $r_a - r_b < d_{ab(i)} < r_a + r_b$ (F1)

- Coordinates of intersection point of circles A_i and B_i are given by –

$$x_{ab(i)} = \left(r_a^2 - r_b^2 + d_{ab(i)}^2\right)/(2d_{ab(i)}); \quad y_{ab(i)} = \sqrt{2d_{ab(i)}^2\left(r_a^2 + r_b^2\right) - \left(r_a^2 - r_b^2\right)^2 - d_{ab(i)}^4} \qquad \text{(F2)}$$

- Circle C_i forms a circular triangle (common area of overlap) with circles A_i and B_i if

$$\left(x_{ab(i)} - d_{ca(i)}\cos\theta\right)^2 + \left(y_{ab(i)} - d_{ca(i)}\sin\theta\right)^2 < r_c^2 \quad \text{and}$$
$$\left(x_{ab(i)} - d_{ca(i)}\cos\theta\right)^2 + \left(y_{ab(i)} + d_{ca(i)}\sin\theta\right)^2 > r_c^2 \qquad \text{(F3)}$$

$$\cos\theta = \left(d_{ab(i)}^2 + d_{ca(i)}^2 - d_{bc(i)}^2\right) \Big/ \left(2d_{ab(i)}d_{ca(i)}\right); \quad \sin\theta = \sqrt{1-\cos^2\theta} \qquad \text{(F4)}$$

N = total number of sampling carried out

N_f = total number of non-overlap cases given by $\sum_{i=1}^{N} I_i$;

P_f = probability of non-overlap

Figure 1. Probability of non-overlap calculation for excavation floor cut-off (overlap of three columns)

3 CONSTRUCTION TOLERANCES

Specified construction tolerances represent the maximum out-of-position or verticality of, for example, any pile or jet grout column (or seal) in any plan direction. They do not represent the average (or expected) absolute[1] inclination or absolute out-of-position, which as explained below will be significantly less stringent.

For analysis it has been assumed that the out-of-position and verticality of piles and jet grout columns can be represented by a normal distribution which is defined by a mean (μ) and standard deviation (σ). When orientation is taken into account, the mean inclination and mean out-of-position for a large number of piles or jet grout columns will be zero. The extremes of the distribution are defined by the construction tolerance. This is shown in Figure 2.

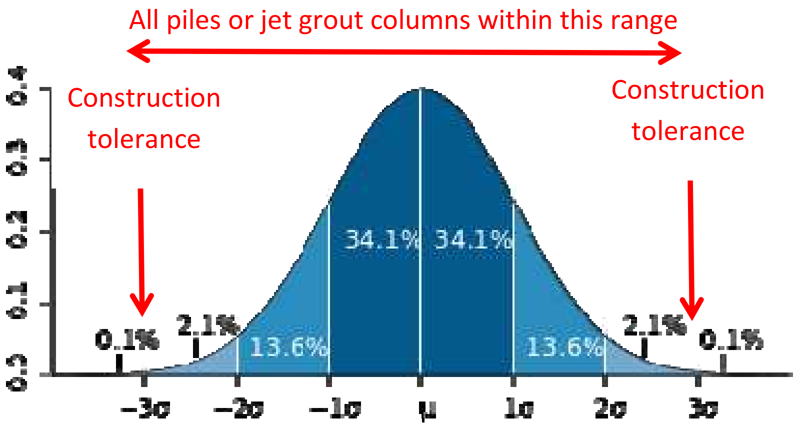


Figure 2. Relationship between construction tolerances and mean and standard deviation for a normal distribution

As shown in Figure 2, 99.73 % of the piles or jet grout columns will lie within three standard deviations of the mean (three sigma rule). That is, the worst out-of-position or verticality of an individual pile or jet grout column (i.e. construction tolerance) will be at three standard deviations from the mean. The dark blue shaded area in Figure 2 represents piles or jet grout columns with inclinations or out-of-position less than one standard deviation from the mean. For the assumed normal distribution, this means that 68.27% of all of the piles or jet grout columns will lie within this area (or within one standard deviation of the mean). Two standard deviations from the mean (medium and dark blue shaded areas) will account for 95.45% of all piles or jet grout columns; and three standard deviations (light, medium, and dark blue shaded areas) will account for 99.73% of all piles or jet grout columns.

When the orientation or direction of the out-of-verticality and position of the piles or jet grout columns are ignored (i.e. only the magnitudes (or absolute values) are considered), a different distribution is obtained. In this case the limits of the distribution are defined at one end by zero out-of-position and exactly vertical and at the other end by the relevant construction tolerances for out-of-position and verticality. The mean (absolute) verticality and out-of-position in this case will be different than set out above. The corresponding standard deviation of this distribution will also be different than set out above. Both of these values can be theoretically calculated from the above normal distributions. These latter values of (absolute) mean or mean magnitude and standard deviation (of magnitude) are perhaps more readily understood and are more easily compared to measured data. The calculated absolute mean (or average) and standard deviations for the construction tolerances set out above are summarised in Table 1. Also included in Table 1 are the absolute verticality and out-of-position values corresponding to 1 (or 68.27 % of piles or jet grout columns), 2 (95.45 %) and 3 (99.73 %) standard deviations from the mean.

The implications of the results in Table 1 can be demonstrated by considering, for example, wall piles with specified verticality and positional tolerance limits of say 1/100 and 25 mm respectively.

The results in Table 1 indicate that for wall piles installed with a verticality tolerance of 1/100, the average (absolute) verticality of piles will be 1/250 with a standard deviation of 1/470. In addition, 68.27 % of the piles installed to this tolerance limit will have a verticality better than 1/165, and 95.45 % of the piles installed will have a verticality of better than 1/120.

[1] The term absolute means there is no reference to orientation or direction. For example, a pile could be inclined at 1/100 to the east or to the west (or in fact any other direction).

Table 1: Calculated statistical parameters based on assumed construction tolerance limits

Tolerance	Tolerance limit	Average (absolute)	Standard deviation	Expected tolerances for stated percentage of piles and jet grout columns		
				68.27 %	**95.45 %**	**99.73 %**
Verticality	1/100	1/250	1/475	1/165	1/120	1/100
	1/75	1/180	1/375	1/120	1/90	1/75
	1/50	1/120	1/250	1/80	1/60	1/50
Position	25 mm	10	5	15	20	25
	50 mm	20	10	30	40	50
	75 mm	30	15	45	60	75

That is, to be reasonably confident that all piles will meet the 1/100 verticality tolerance, then on average piles will need to achieve a verticality of better than 1/250. This implies that the target verticality should be significantly more stringent (say 1/250) than the specified limit of 1/100. A target of 1/250 is a very stringent construction tolerance which is not easily achieved with piling. In the authors' experience with CFA piling works on a large number of basement retention projects, conventional CFA piling equipment using a relatively stiff auger and appropriately prepared working platform can typically achieve average verticality of piles of about 1/00 to 1/125 with some piles having verticality of 1/75 and a few as low as 1/50. On the basis of Table 1 this indicates verticality tolerances of perhaps 1/50 or at best 1/75. This suggests that the use of conventional CFA equipment which are commonly used to form pile walls is unlikely to achieve a specified verticality tolerance of 1/100.

The authors' experience with jet grouting has included direct measurement of verticality of columns using an inclinometer in the monitor. These measurements indicated an average verticality of about 1/100, which based on Table 1 indicates a verticality tolerance of 1/50.

Therefore, in the analysis set out below, verticality tolerances of 1/100, 1/75 and 1/50 piles and jet grout columns/seals have been analysed.

Similarly, to achieve a positional tolerance of 25 mm, piles would need to be installed with an average (absolute) out-of-position of 10 mm (refer Table 1). This would likely require use of an appropriately constructed guide wall with relatively tight clearance between the auger and the guide wall. In our experience it would be more common to achieve an average out-of-position of more than 10 mm using a guide wall. To achieve a positional tolerance of 75 mm for piles constructed without a guide wall would require piles to be installed with an average (absolute) out-of-position of 30 mm.

For jet grouting, there is a similar control over the position of the column, and hence similar potential for the columns to be out-of-position. Therefore, positional tolerances of 50 mm and 75 mm for piles and jet grout columns/seals have been assumed.

It has also been assumed that the CFA piles, jet grout floor columns and jet grout seals have been installed at their minimum design diameters. It is likely that the installed diameter of the piles, jet grout columns and jet grout seals will be variable and will often be greater than these minimum diameters. Larger installed diameters for the jet grout columns and jet grout seals will generally act to reduce the area of untreated ground. As a result the probability of areas of untreated ground being present will likely be less than presented in the calculations below. However, for design it would generally be imprudent to rely on larger installed diameters.

4 MONTE CARLO SIMULATION METHOD

In the context of the present study, the Monte Carlo simulation (MCS) method involves random sampling of possible locations of the grout column centres at a selected depth below installation level (e.g. top or bottom of jet grout floor).

Possible locations (coordinates) of a grout column centre are generated based on random variants taken to follow normal distributions $N(\mu, \sigma)$, with mean μ and standard deviation σ. If a sufficiently large number of sampling is carried out, μ corresponds to the exact location of a column centre or to the location when construction tolerances in terms of column verticality, out-of-position, column diameter etc. are not taken into account.

The column diameters have been assumed to be constant at a specified value. If column verticality, *v*, and out-of-position location, *e,* each follow the three-sigma rule (i.e., variations of inclination and out-of-position lie within three standard deviation of the mean), then one standard deviation, σ, of the column location at a given depth *H* below installation level is given by the following equation:

$$\sigma = \sqrt{(v/3 \cdot H)^2 + (e/3)^2} \quad (2)$$

4.1 Random Number Generation

Generation of random variables forms a key component of the MCS method. It is common to generate distribution variants based on uniform random number variants. For example, Normal distribution variants for the coordinates of the grout column centres can be generated as follows in MS Excel software:

1) Generate uniform random variants u_i using function RAND( );
2) Generate standard normal random variants s_i using NORM.S.INV(u_i);
3) Generate coordinates for the column centre A, for example, as follows

$$(x_{ai}, y_{ai}) = \left((\mu_{xA} + \sigma_{xA} \cdot s_i), (\mu_{yA} + \sigma_{yA} \cdot s_{i+1})\right) \quad (3)$$

where $\left(\mu_{xA}, \mu_{yA}\right)$ are the coordinates of the exact location of the centre of column A.

4.2 Probability of Non-overlap based on MCS

The probability of non-overlap for the excavation wall can be calculated using the flow chart presented in Figure 1. For each sampling stage, the indicator function I_i takes a value of 1 if the conditions of column overlap are not satisfied. The probability of non-overlap is given by the ratio of the summation of indicator function I_i to the total number of samples (Rubinstein 1981).

It is noted that larger the number of samples, closer the value of μ is to the exact location of a column and more accurate the estimate of probability of non-overlap.

5 EXAMPLES

To illustrate the calculation of probability of non-overlap of columns (i.e., the probability of cut-off being ineffective), three example cases of verticality and two cases of out-of-position distances have been analysed. For each of the following combinations of construction tolerances, it is assumed that columns can be installed such that each variation in the tolerances follows the three-sigma rule:

- Column verticality of 1 in 100 (1.0%), 1 in 75 (1.33%) and 1 in 50 (2.0%);
- Column centre off-sets of ±50 mm and ±75 mm out-of-position

Examples of the excavation grout floor and the excavation grout wall layouts are presented below.

5.1 Excavation floor

An example cut-off floor comprising jet grout columns on a triangular grid with column diameters of 2.5 m, 2.2 m and 2.2 m and a design centre to centre spacing of 1.9 m has been assumed. The top of the jet grout floor is assumed to be at a depth of 10 m below the column installation level. The calculated probability of non-overlap for the floor is presented in Table 2, based on 10 000 simulations.

Figure 3 presents a plot of generated random centres for columns A, B and C for a combination case of construction tolerances with verticality of 1 in 75 and out-of-position of ±75 mm (Case 9 in Table 2).

Table 2: Probability of non-overlap of three columns based on MCS, calculated for a depth of 10 m

Case	Verticality	Out-of-position	σ	Probability of non-overlap* (%)
1	0	±50 mm	0.01667	0.000
2	0	±75 mm	0.02500	0.050
3	1 in 100	0	0.03333	0.560
4	1 in 75	0	0.04444	2.95
5	1 in 50	0	0.06670	11.88
6	1 in 100	±50 mm	0.03727	1.21
7	1 in 100	±75 mm	0.04167	2.22
8	1 in 75	±50 mm	0.04747	4.02
9	1 in 75	±75 mm	0.05099	5.35

Notes: * Based on 10 000 samples

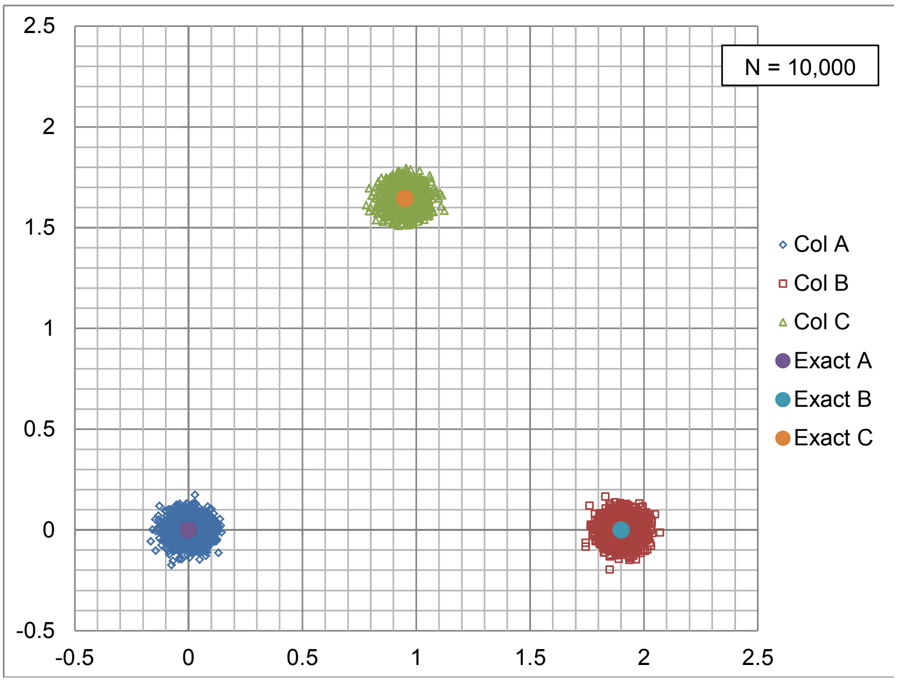


Figure 3. Generated random centres for three columns A, B and C at a depth of 10 m below installation level, and for construction tolerances for verticality of 1 in 75 and out-of-position of ±75 mm (solid points show exact centre locations)

5.2 Excavation wall

Table 3 presents the calculated probability of non-overlap for an example of cut-off wall, based on 10 000 simulations. The example layout comprises two 1200 mm diameter piles A and B installed at spacing of 1.3 m centre-to-centre and one 500 mm diameter grout column C installed at 0.715 m from the centre of piles A and B. It has also been assumed that a minimum overlap ε of 10 mm would be required between the grout column C and piles A or B.

Table 3: Probability of non-overlap of two adjacent columns based on MCS, calculated for a depth of 10 m

Case	Verticality	Out-of-position	σ	Probability of non-overlap* (%)
1	0	±50 mm	0.01667	0.000
2	0	±75 mm	0.02500	0.040
3	1 in 100	0	0.03333	0.960
4	1 in 75	0	0.04444	5.30
5	1 in 50	0	0.06670	20.76
6	1 in 100	±50 mm	0.03727	2.05
7	1 in 100	±75 mm	0.04167	3.81
8	1 in 75	±50 mm	0.04747	7.09
9	1 in 75	±75 mm	0.05099	9.35

Notes: * Based on 10 000 samples

6 CLOSING REMARKS

A spreadsheet method for estimating the probability of not achieving overlap between jet grout columns (for jet grout floors) and or jet grout seals and piles (for walls) which takes into account construction tolerances on column location and verticality is presented. The method is illustrated using two example column layout configurations and a range of construction tolerances. The relationship between construction tolerances and average verticality, and position of jet grout columns and piles is discussed, with a conclusion that specified construction tolerances imply a more stringent condition than is typically envisaged by the designer or measured. These more stringent tolerances need to be considered when designing jet grout column layouts.

Whilst the analysis presented herein assumes a constant column or pile diameter, this is unlikely to be the case in practice. Variations in the column diameters can be incorporated into analysis by a relatively simple modification (which comprises the generation of random variants for radii of the circle) in the flow chart process in Figure 1.

REFERENCES

Fewell, M.P. (2006). Area of Common Overlap of Three Circles, Report number DSTO-TN-0722, Maritime Operations Division, Defence Science and Technology Organisation, Australia, <http://dspace.dsto.defence.gov.au/dspace/handle/1947/4551> (Sep. 2014).

Rubinstein, R.Y (1981). Simulation and the Monte Carlo Method, John Wiley & Sons Inc., Toronto.