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Use of Pressure Relief Wells to Optimise Ground Improvement Layer Thickness in Deep Excavations

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ABSTRACT: Deep excavations in soft ground often need stabilization with ground improvement (GI). One of the methods to improve the ground is to use Jet Grouting Piles (JGP) or Deep Soil Mixing (DSM). JGP and DSM are achieved by mixing the soil with cement and water, generating a structure that performs well under compression forces but not under tension forces. These ground improvement blocks provide larger passive resistance thereby reducing wall displacements. Due to the above mentioned behaviour of ground improvement, one of the necessary requirements for successful a design is that no tension forces are allowed in any zone of the ground improvement block. This paper discussed how pressure relief wells inside the excavation are used in order to decrease the tension strains in the ground improvement block and demonstrated it through a series of 2D numerical analyses.

KEYWORDS: Deep Excavation, Ground Improvement, DSM, JGP, Pressure Relief Wells, Numerical Analysis.

1. INTRODUCTION

Deep excavations are excavations that exceed 6 meters in height. There are several methods to construct excavations such as slopes, open cuts, retaining structures, etc.

Deep excavations with retaining structures in presence of soils formations with low geotechnical parameters (strength and stiffness) often used ground improvement techniques. There are several reasons for this; decreasing forces in the retaining structure, preventing large wall displacements, preventing damage to existing structures, etc. This is applied mostly in urban areas because it is important to reduce wall displacements to avoid damage to existing structures such as surrounded building, underground utilities, adjacent roads, etc.

Ground improvement is applied before the excavation starts, so this improved block is active before the excavation commences and reduces the wall displacements.

Several design checks need to be carried out in deep excavations in the temporary case (while the excavation is being performed), such as:

ULS requirements:
- Structural capacity of any structure used in temporary case
- Toe-in capacity of the retaining structure
- Uplift verification
- Base heave
- Geotechnical capacity of temporary foundations elements

SLS requirements:
- Displacements in the retaining structure

When ground improvement such as JGP or DSM is used some specific design requirements shall be verified as discussed further in detail in paragraph 2.2.

This paper will show that for deep excavations under certain geological profiles pressure relief wells can be used as an alternative solution to avoid excessive ground improvement thickness. This will be demonstrated using 2D numerical analysis of a deep excavation of a TBM launching shaft of an MRT Line in Singapore where this solution has been used. The base solution and two alternatives solutions, with and without pressure relief wells, will be discussed in this paper. Finally the cases where the optimized solution can be applied will be discussed.

2. DEEP EXCAVATIONS WITH GROUND IMPROVEMENT

Where deep excavations using retaining structures are performed in presence of soil formations with low geotechnical parameters, such as soft clays, the retaining structures are subjected to high soil stresses. Since the soil stresses increase with the depth, deeper excavation results in increased wall deflections and forces in the retaining structures. In these situations ground improvement is commonly used. There are several techniques to improve the properties of the ground prior the excavation, for example densification techniques, reinforcement techniques, replacements techniques, mixing techniques, etc. This paper will be focused on mixing techniques such as Deep Soil Mixing and Jet Grouting Piles.

2.1 Deep Soil Mixing and Jet Grouting piles

The Deep Soil Mixing method (DSM) was invented in Japan and Scandinavia. Its use is growing across the world in strengthening and sealing weak ground. The method helps to achieve significant improvement of mechanical and physical properties of the existing soil, by mixing with water and cement or compound binders to become a so-called soil-mix (or soil-cement). The stabilised soil material that is produced generally has a higher strength and lower permeability than the native soil. The composite ground block is produced with water, soil and cement.

Jet Grouting Piles (JGP) is a construction process that uses a high-pressure fluid jet (generally 20 – 40 MPa) at a depth in a borehole, to break up and loosen the soil at depth in a borehole and to mix it with a self-hardening grout to form columns, panels and other structures in the ground. The parameters for the jet-grouting process and the desired final strength of the treated soil depend on a number of characteristics, such as the soil type, the technique used and the required solution.

Both cases, DSM and JGP, are ground improvement techniques that use a mix of soil, cement and water. In both cases the ground improvement does not have any tension resisting elements (such as steel reinforcement), thus generating a structure that behaves well under compression forces however cannot resist any tension forces.

These types of ground improvements techniques are commonly used in the soft clays of Singapore, such as the Kallang formation. Figure 1 shows a deep excavation in Kallang Formation with the exposed ground improvement block below the base slab.

2.2 Stability requirements in Deep Excavations with ground improvement

As stated in the introduction, there are design checks to be carried out when using ground improvement in deep excavations such as:

a) Adequate bounding capacity between the ground improvement and the retaining structures and/or existing piles.
b) No tension forces develop in the treated ground during all stages of construction.

Figure 1 Deep excavation in Singapore with exposed ground improvement

The first check is required due to actions that generate high shear stresses between the underground structures and the ground improvements, these actions are:

1. Unloading of the soil below the formation level causing the soil underneath the final excavation level to heave.
2. Uplift force of the groundwater below the formation level as shown in Figure 2. This action is common when the water table is at or near the ground level and there is a granular soil formation below the final excavation level. Granular soil formation makes reference to soil type allow water to flow easier such that no excess pore water pressure develops under changes in stresses. This uplift force tends to heave the soil underneath the formation level.

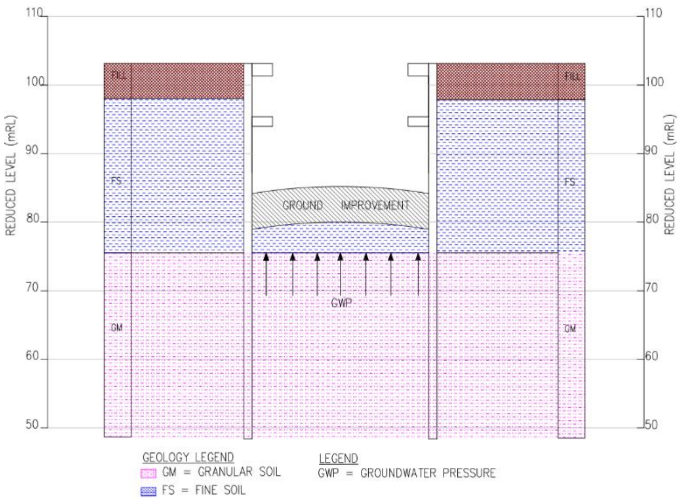

Figure 2 Uplift force below the formation level in a deep excavation

One of the possible methods to decrease the uplift force of the groundwater inside the excavation is to include pressure relief wells, which helps to decrease the groundwater table and therefore the uplift force. This paper focusses on deep excavations with ground improvement below the formation level where the uplift verification is satisfied without pressure relief wells while the tension force requirement in the ground improvement is not.

2D Numerical analysis is used to check the tension force in the ground improvement with and without the use of pressure relief wells.

3. NUMERICAL ANALYSIS

As stated in the previous paragraph, 2D Plaxis numerical analysis is performed to show that the pressure relief wells are used as an alternative solution to decrease the tension forces in the ground improvement block.

3.1 Geometry of the deep excavation and construction sequence of the excavation

The excavation of a launching shaft is for a TBM launching in the Thomson Eastern Region Line in Singapore. The dimensions of the shaft are 25.70 meters length x 25.70 meters wide x 18.90 meters depth. The construction sequence of the excavation is:

1. Install retaining structure (DWall).
2. Install ground improvement below formation level.
3. Excavate to the base of the first reinforced concrete waler beam RCW1.
4. Cast first reinforced concrete waler beam RCW1.
5. Excavate to second reinforced concrete waler beam RCW2.
6. Cast second reinforced concrete waler beam RCW2.
7. Excavate to temporary base slab.
8. Cast temporary base slab.
9. Launch TBM.

The initial proposed thickness of the ground improvement is five meters (5 m.). The properties of the structural elements are presented in the Table 1 below:

Table 1 Properties of the structural elements

Structural Element	**Thickness (m)**	**Axial Stiffness (kN/m^3)**	**Bending Stiffness (kN.m/m^2)**	**Element type**
Diaphragm Wall	1200	3.96E+07	3.32E+06	Plate
RCW1	3mx1,8m Beam	2.44E+05	-	Fixed end Anchor
RCW2	3mx1,4m Beam	1.90E+05	-	Fixed end Anchor
Temporary Slab	0,5	1.65E+07	3.44E+05	Plate

3.2 Geological profile and geotechnical properties

The shaft is located at the south east side of Singapore, where there are two main geological formations: Kallang Formation and Old Alluvium.

Kallang Formation: these deposits are of marine, alluvial, littoral and estuarine origin. The most important unit of the Kallang Formation is the Marine Clay, which is an under to normally consolidated soft, silty, kaolin-rich clay. In general the clay content is high at around 60 to 70%.

Old Alluvium: Geologically the Old Alluvium is thought to represent a deltaic and braided river deposit. Soil type varies from slightly clayey sand through sandy and clayey silts to silty clay with the predominant soil type being medium dense to very dense silty to clayey sand. Bands of coarse subangular and subrounded gravel can locally occur with a maximum recorded clast size of 60mm.

Table 2 below presents the geotechnical parameters of the soil encountered and used in the numerical analysis.

Table 2 Geotechnical properties of the soil formations

Soil Layer		γ_s (kN/m^3)	ϕ' (°)	c' (kPa)	C_u (kPa)
Fill		20	30	0	-
Kallang Formation	Fluvial Sand (F1)	20	30	0	-
	Fluvial Clay (F2)	19	24	0	1.25.(120-Z) *
	Estuarine Deposits (E)	17	22	0	0.75.(126.67-Z) *
	Upper Marine Clay (UMC)	16	22	0	0.33.(161.67-Z) *
Old Alluvium	O(D) [10<N<30]	20	32	1	100
	O(C) [30<N<50]	20	35	5	200
	O(B) [50<N<100]	21	35	5	300
	O(A) [N>100]		35	10	400

Soil Layer		E_u (kPa)	E' (kPa)	K_0	k (m/s)
Fill	Fill	-	12,000	0.5	1×10^{-05}
Kallang Formation	Fluvial Sand (F1)	-	560(113.5-Z)	0.5	1×10^{-05}
	Fluvial Clay (F2)	375(120-Z)	$E_u/1.2$	0.7	1×10^{-08}
	Estuarine Deposits (E)	187.5(126.67-Z)	$E_u/1.2$	0.63	1×10^{-08}
	Upper Marine Clay (UMC)	99(161.67-Z)	$E_u/1.2$	0.63	1×10^{-09}
Old Alluvium	O(D) [10<N<30]	30,000	$E_u/1.2$	0.8	1×10^{-08}
	O(C) [30<N<50]	80,000	$E_u/1.2$	0.8	1×10^{-08}
	O(B) [50<N<100]	150,000	$E_u/1.2$	0.8	1×10^{-08}
	O(A) [N>100]	200,000	$E_u/1.2$	0.8	1×10^{-08}

* Note = Z denotes the depth in reduced level.

Figure 3 shows a cross section of the launching shaft that is part of an MRT Line in Singapore with the geological formation encountered. It is important to underline that the water table is found to be 1 to 2 meters below the ground level. For the analysis this has been defined at the ground level.

As described above, materials of the Old Alluvium (OA) formation are clayey sand through sandy and clayey silts to silty clay with presence of gravel, so this formation's behaviour has been defined as drained. On the other hand all the soil types of the Kallang formation (KF) except Fluvial Sand (F1) have been defined with undrained behaviour.

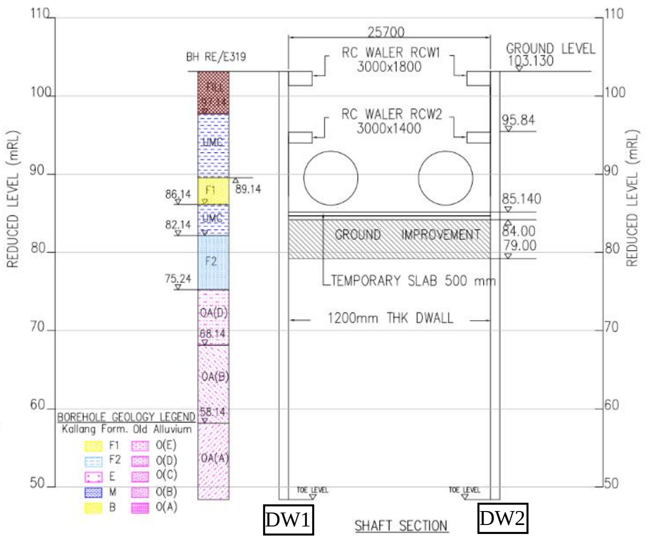

Figure 3 Cross section of the TBM launching shaft with geo profile

For the ground improvement block the following properties in Table 3 below have been used:

Table 3 Properties of the Ground improvement

Layer	E (kPa)	Cu (kPa)
Ground Improvement (GI)	280,000	800

4. RESULTS OF THE NUMERICAL ANALYSIS

4.1 Base Solution

As stated in the paragraph 3.1, the initial proposed solution was to install a 5 meters permanent ground improvement layer below the temporary base slab. The following graphs show the displacements and bending moments in the DW2 (Figure 4) during the final stage (casting of the temporary base slab).

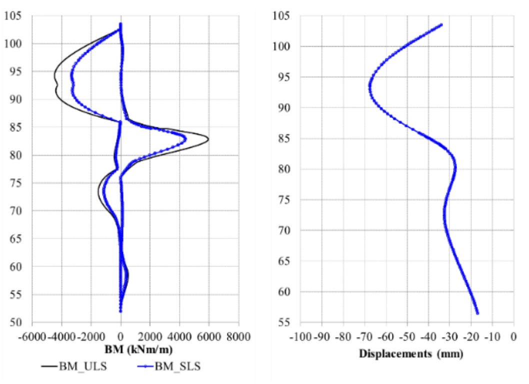

Figure 4 Wall Forces and Displacements of the DWall

The ULS stability checks and SLS limits wall deflections are presented in the Table 4.

Table 4 ULS & SLS checks for the base solution

ULS check	Safety factor
Toe-in	2
Base Heave	N.A.
Uplift	1.26
Bonding check Ground improvement - ERSS	1.4
ULS check	**ε_{xx} (-)**
Tensile strains in the ground improvement block	1.78E-03

SLS check	Allowable Displ. (mm)	Max Displ. (mm)
Horizontal displacement in the DWall	130	68

As shown in the above tables, with the base solution the only check that is not passed is the tensile strains in the ground improvement block. Figure 5 presents the deformed mesh in the final stage as well as the horizontal strains in the ground improvement layer.

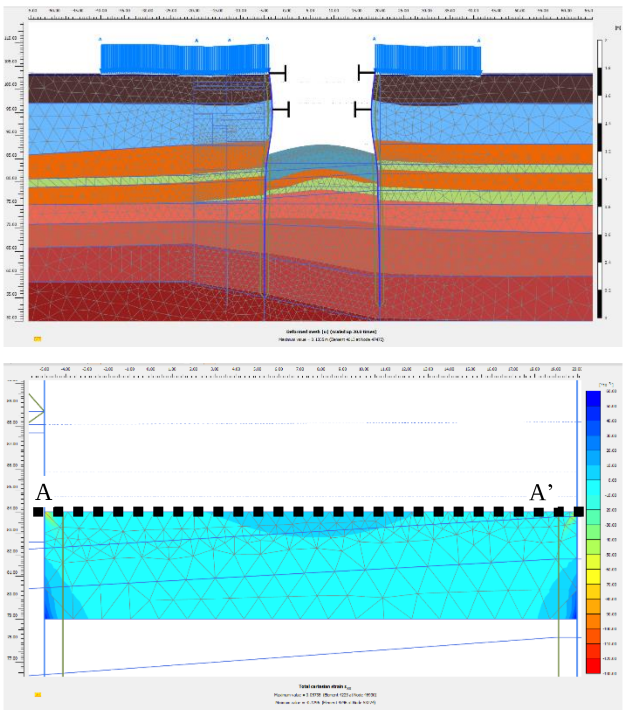

Figure 5 Deformed mesh and horizontal deformations in the ground improvement block during the last stage

The maximum horizontal strains in the ground improvement block are obtained from the top of the layer as showed in the Figure 5. Figure 6 shows the horizontal strains in the top of the ground improvement for section A-A'.

As it is presented in Figure 7, there are tensile strains in the ground improvement block. Because of that, two alternatives solutions are proposed, these alternatives solutions are presented in sections 4.2 and 4.3 below.

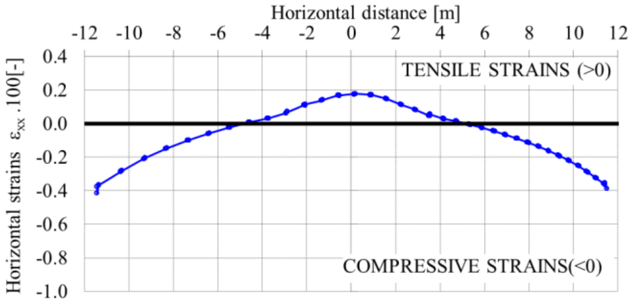

Figure 6 Horizontal strains in the top of the ground improvement block with 5 meters of GI thickness

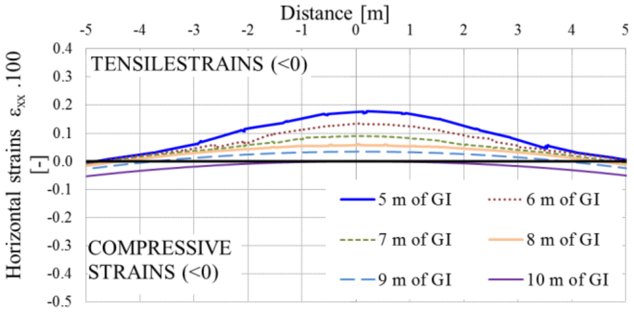

Figure 7 Horizontal strains in the top of the ground improvement layer with different thickness

4.2 First alternative solution: increment of the thickness of the ground improvement

When the thickness of the ground improvement is increased, the stresses are distributed in a higher spam resulting in a decrease of the tensile strains on the top of the ground improvement layer.

The final solution is carried out through an iterative approach: the thickness of the ground improvement layer is increased to achieve compressive strains in the top of the layer. The next figure shows the horizontal strains with the different ground improvement thickness.

The successful solution for the first alternative is achieved with 10 m. thickness of ground improvement (increment of 5 meters from the base solution). It is important to highlight that, 10 meters of ground improvement, result in a higher safety factor for the rest of the ULS checks and SLS shown in

Table **4** comparing with the base solution.

4.3 Second alternative solution: using of pressure relief wells inside the excavation.

When pressure relief wells are used, the uplift force of the groundwater (in the Old Alluvium formation) below the final excavation level is decreased according to the groundwater flow analysis.

In this alternative, the construction sequence of the excavation is similar to the construction sequence presented in paragraph 3.1 with the only difference being the installation and activation of pressure relief wells (from the ground level up to 5 meters below the old alluvium stratum) after installation of the DWalls. Figure 8 shows a cross section with the pressure relief wells.

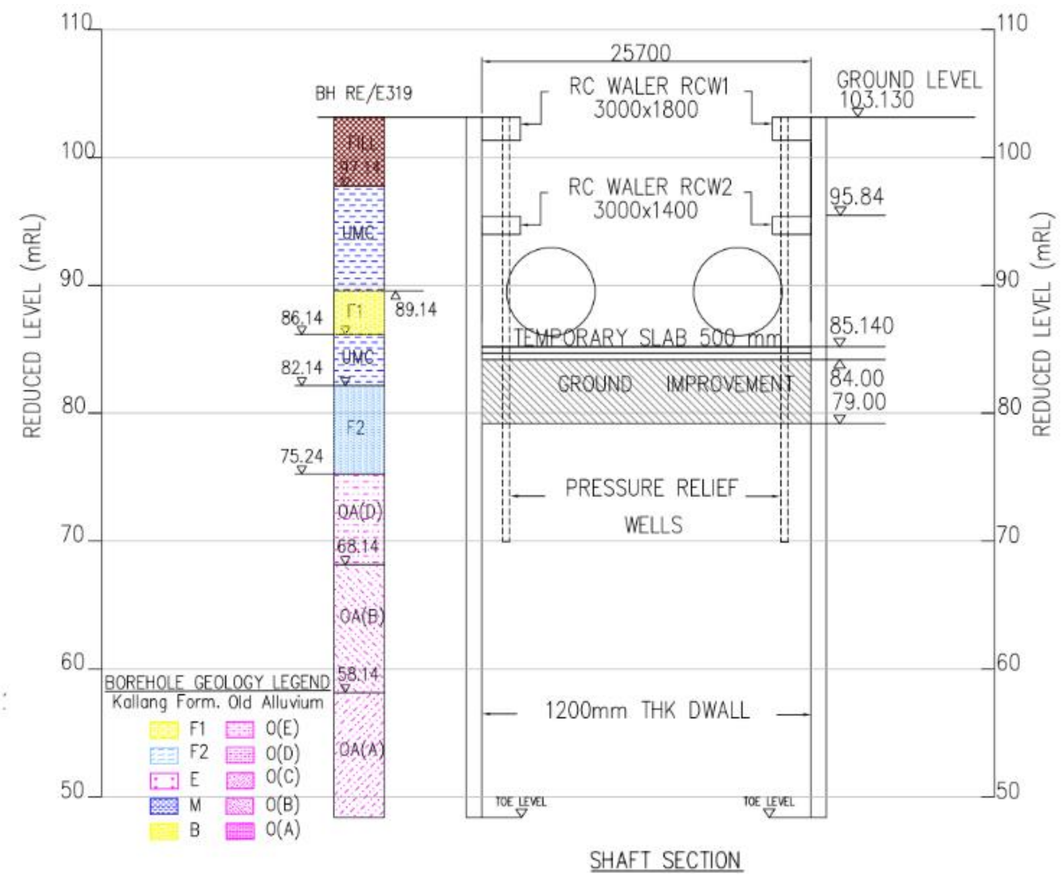

Figure 8 Cross section of the TBM launching shaft with geo profile in the second alternative (use of pressure relief wells)

Table 5 summarises the results of ULS and SLS checks.

Table 5 ULS & SLS checks for the second alternative solution

ULS check	**Safety factor**
Toe-in	2
Base Heave	N.A.
Uplift	3.79
Bounding check Ground improvement - ERSS	3.7
Tensile strains in the ground improvement block	No tensile strains presented

LS check	**Allowable Displ. (mm)**	**Max Displ. (mm)**
Horizontal displacement in the DWall	130	79

Figure 9 shows no horizontal tensile strains in the top of the ground improvement layer.

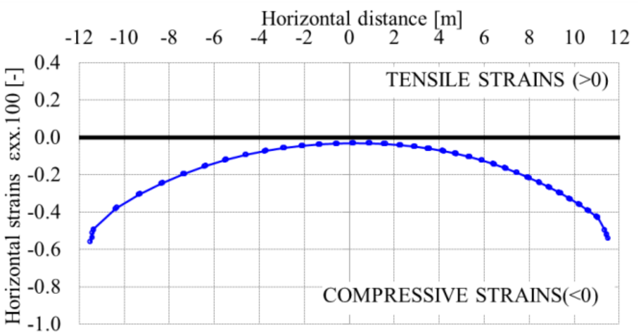

Figure 9 Horizontal strains in the top of the ground improvement block with 5 meters of GI thickness and use of pressure relief wells

4.4 Comparison between the alternatives.

The first alternative is to increase the thickness of the ground improvement block and the second option is the installation of relief wells from the ground level to below the formation level. Both methods decrease the tensile strains in the ground improvement block. Also both alternatives pass all the ULS and SLS checks so both solutions can be considered for the design of the shaft.

Figure 10 shows the horizontal strains distribution in the top of the ground improvement block for both alternatives, it is clear that in both alternatives there are not tensile trains in the top of the ground improvement.

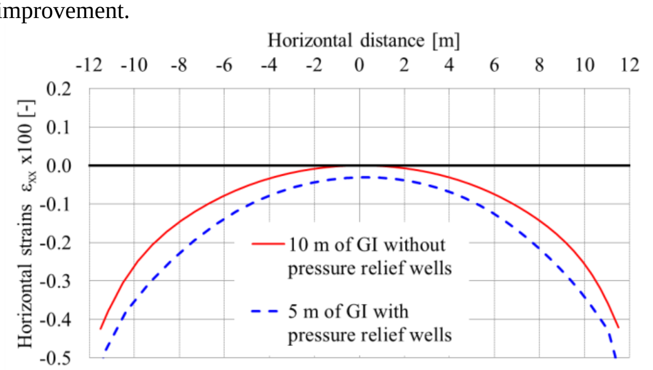

Figure 10 Horizontal strains in the top of the ground improvement block for first and second alternative

However the main difference can be observed comparing the volume of ground improvement and the use of pressure relief wells. The first alternative solution uses:

Ground improvement volume:

Vol = $(25.7m)^2$ x 10m = 6604 m^3

Pressure relief wells = No pressure relief wells used.

On the other hand, the second alternative solution uses:

Ground improvement volume:

Vol = $(25.7m)^2$ x 5m = 3302 m^3

Pressure relief wells = 16 pressure relief wells (5 meters spacing between the wells).

Regarding the above comparisons it can be concluded that the second alternative, with use of pressure relief wells, it is the most cost and time effective because it saves around 3300 m^3 of ground improvement with the use of just 16 pressure relief wells.

5. CONCLUSION

Deep excavations with retaining structures in presence of soils formations with low geotechnical parameters often used ground improvement techniques like DSM and JGP. These ground improvement techniques performs well under compression forces but not under tension forces. Due to the above mentioned one of the necessary requirements for successful design is that no tension forces are allowed in any zone of the ground improvement block. In this paper has been presented a method to design efficiently a deep excavation with ground improvement where tensile strains are presented in the ground improvement block. The presented method is tested using 2D numerical analysis of the deep excavation. The following conclusions are made:

(1) When a deep excavation occurs, tensile strains in the top of the DSM or JPG layer can be presented. This is more likely to happen when: (a) There is a granular soil formation below the final excavation level and (b) The water table is at or near the ground level.

(2) In order not to allow tensile strains in ground improvement blocks, it can be proposed to increase the thickness of the layer of the ground improvement or use of pressure relief wells to decrease the uplift force. Both methods reduce the tensile strain in the improved ground.

(3) Use of pressure relief wells can be a cost and time effective method, saving large volume of ground improvement.

6. REFERENCES

Chang-Yo Ou (2006) Deep Excavations. Theory and Practice. Departament of Construction Engineering. National Taiwan University of Science and Technology. Taipei, Taiwan.

Land & Transport Authority (2010) "Civil Design Criteria for Road and Rail Transit System". E/GD/09/106/A1.

Taipei Zoo, Taipei, Taiwan (1996) "Analysis of Deep Excavation with Column Type of Ground Improvement in Soft Clay". Journal of Geotechnical Engineering 09/1996; 122(9). DOI: 10.1061/(ASCE)0733-9410(1996)122:9(709).

Tian, H, Tan, S.A.; Tjahyono, S.; Lim, C.H.; Tanaka, H. (2010) " Ground improvement for deep excavation of City Square Mall". Geotechnical Society of Singapore - International Symposium on Ground Improvement Technologies and Case Histories, ISGI'09.