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Tensile strength behaviour of Ground Improvement and its importance on deep excavations using deep soil mixing.

Le comportement de la résistance à la traction de Ground Improvement et son importance pour les excavations profondes utilisant un mélange de sol en profondeur.

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ABSTRACT: Deep excavations in soft ground often require additional stabilization through ground improvement (GI). Some of the common methods to improve the ground are Jet Grouting Piles (JGP), Deep Soil Mixing (DSM) or Wet Speed Mixing (WSM). JGP, DSM and WSM 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 and thereby reduce wall displacements. Ground improvement in deep excavation is an efficient method to improve the performance of the soil structure for temporary stage, however it results in a significant cost for underground constructions in soft clays.
This paper focuses on the selection of appropriate ground improvement parameters during design phase with focus on the tension strength of ground improvement. This is showed with the results of indirect splitting tests from samples retrieved of deep soil mixing in kallang formation in Singapore. The effect of tensile strength is showed through a 2D numerical analysis of a real TBM shaft excavation in Singapore.

RÉSUMÉ: Les excavations profondes dans des sols meubles nécessitent souvent une stabilisation supplémentaire par l'amélioration des sols. Parmi les méthodes les plus courantes, on peut citer les piles à jet de coulis (JGP), le mélange en profondeur du sol (DSM) ou le mélange à vitesse humide (WSM). JGP, DSM et WSM sont obtenus en mélangeant le sol avec du ciment et de l'eau, générant une structure qui fonctionne bien sous des forces de compression mais pas sous des forces de tension. Ces blocs d'amélioration des sols offrent une plus grande résistance passive et réduisent ainsi les déplacements de paroi. L'amélioration des sols lors de l'excavation en profondeur est une méthode efficace pour améliorer les performances de la structure du sol en phase temporaire, mais elle entraîne un coût important pour les constructions souterraines en argile meuble.
Cet articlese concentre sur la sélection des paramètres d'amélioration du sol appropriés pendant la phase de conception, en mettant l'accent sur la résistance à la traction de l'amélioration du sol. Ceci est démontré par les résultats des tests de traction indirect d'échantillons extraits du mélange de sol en profondeur dans la formation geologique de Kallang à Singapour. L'effet de la résistance à la traction est démontré par une analyse numérique 2D d'une excavation réelle de puits de tunnelier à Singapour.

Keywords: Ground Improvement, Tensile strength, Deep Excavations, 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

When ground improvement such as JGP or DSM is used some specific design requirements shall be verified as discussed further in detail in paragraph 2.1.

This paper focuses on how the selection of appropiate parameters of ground improvement, with special attention to the tensile strenght, can lead to a more economical design. This is showed by first including some indirect splitting tests (or Brazilian tests) results on DSM samples and secondly by applying those results in a numerical analysis.

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 DSM and JGP.

2.1 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.

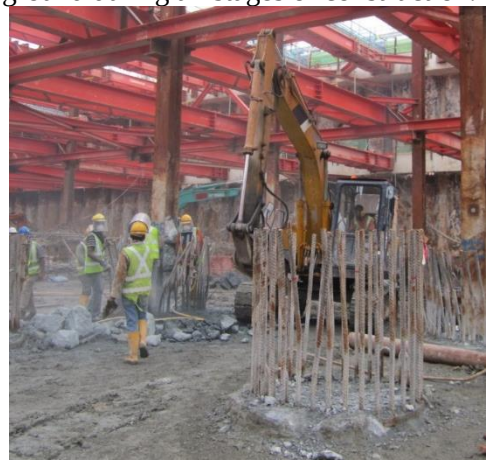

Figure 1. Deep excavation in Singapore with exposed ground improvement

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. 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.

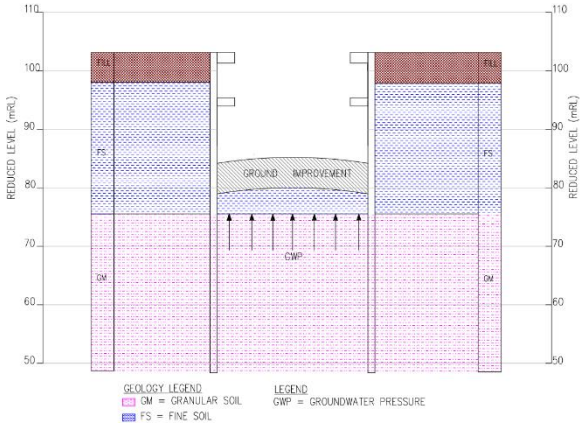

Figure 2. Uplift force below the formation level in a deep excavation

One of the possible methods to decrease the uplift force of the groundwater inside the excavation is to include pressure relief wells (Pittaro, 2017), which helps to decrease the groundwater table and therefore the uplift force.

This paper actually focuses on the selection of proper tensile strength of GI can help to reduce the thickness of GI and hence to do a more economical design.

3 TENSILE STRENGTH IN GROUND IMPROVEMENT

Ground Improvement tensile strenght has been studied previosuly and concluded that the tensile strenght can be related to the unconfined compressive strenght such as

$$ft = fc \cdot 0.13 \quad (1)$$

Where ft is the tensile strenght of the ground improvement and fc is the unconfined compressive strenght of the same soils cement mixing (Huwawen, 2009). In this section the results of indirect splitting tests are showed.

3.1 Indirect Splitting Tests

Indirect splitting test or Brazilian test is a popular laboratory test that measures the tensile strenght property of (usually) rocks by aplying a compression line load in the circunference of a cilynder sample. In the below picture is depicted a typical sketch for a brazilian test used for ground improvement in this paper.

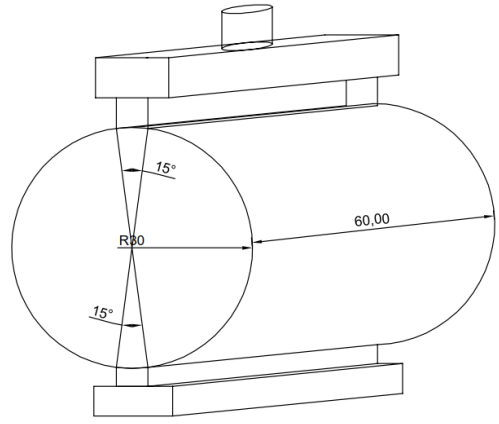

Figure 3. Typical Brazilian test sample and bearing blocks.

3.2 Test procedure and sampling preparation

ASTM 3967 was followed for the brazilian tests, samples using a diameter/length relation of 1 were tested (diameter = length = 60 mm). The application of load was followed by a prescribed fixed vertical displacement of 0.5 mm/min.
The samples were obtained at a depth of about 25 to 30 meters below ground level. The original ground conditions is Marine clay with a characteristicshear strength as low as 5 to 10 kPa.

Figure 4. GI sample set up before testing.

Due to this ground improvement using deep soil mixing was used. The below GI parameters were used to mix the ground:

Table 1. DSM operation Parameters

ITEM	OPERATION PARAMETERS	UNIT	VALUE FOR DSM COLUMN
1	Diameter	mm	1750
2	Spacing (c/c)	mm	1260
3	Grout Flow Rate	l/min	147 (±20)
4	Rotation Rate	rpm/min	16 - 18
5	Grout Pressure	bar	1 - 4
6	W/C Ratio		1 : 1
7	Grout Density		1.51 (±0.03)

3.3 Test Results

10 samples were tests, the results of the tensile strenght were obtained by correlating the tensile strength with the applied load using the below equation :

$$ft = \frac{2.P}{\pi.D.L} \quad (2)$$

Where P is the compression load obtained on top of the sample, D is the sample diameter (60mm) and L is the sample length (60mm). Below there is a a typical crack developed at the center of the sample after the tension capacity has been exceeded.

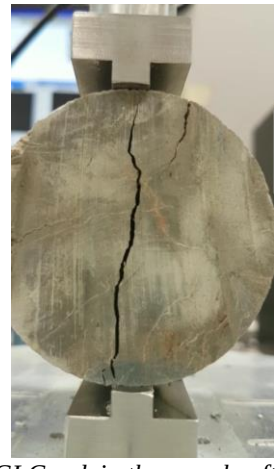

Figure 5. GI Crack in the sample after failure.

The results of the 10 samples are summarized in the below table:

Table 2. Tensile strength results

Sample	Max Applied Force (N)	Max Tensile strength (kPa)
1	3600	657
2	3348	611
3	3574	652
4	3348	533
5	3048	556
6	1881	343
7	3114	568
8	2481	453
9	2266	414
10	2434	444

3.4 Discussion Test Results

The maximum tensile strength results from the splitting tests are above 400 kPa, as stated in the section 2 no tensile strength is usually used during design.

In the below graph is showed the vertical load vs tensile stress.

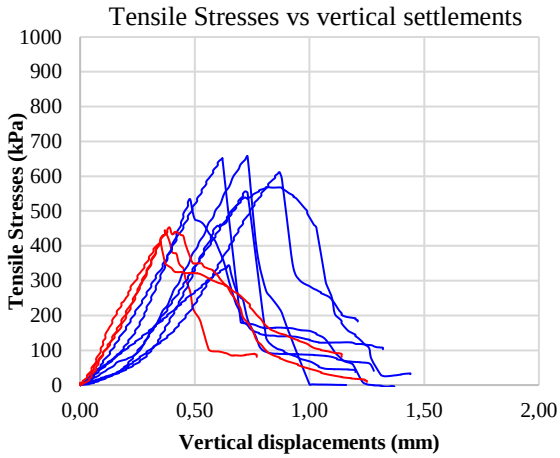

Figure 6. Tensile stresses vs vertical displacements.

In figure 6, graphs with 2 different colours are showed as it is highlighted that the GI has been retrieved from two different layer of kallang formation. In blue, are presented the samples from lower marine clay (LMC) and in red the samples retriedved from fluvial clay (F2). On the in situ condition, the fluvial clay layer presents more strength resistance than the Marine clay. The author believes that this can be one reason that produces more difficulty when mixing with cement and therefore less tensile strength. The above is showev in figure 7.

It is also clear from figure 6 the brittle behaviour of ground imrpovement in tension, this is a factor to be considered in design as post peak failure cannot be accepted, hence if tension strength is used, the designer must ensure that the deformation is within the elastic range.

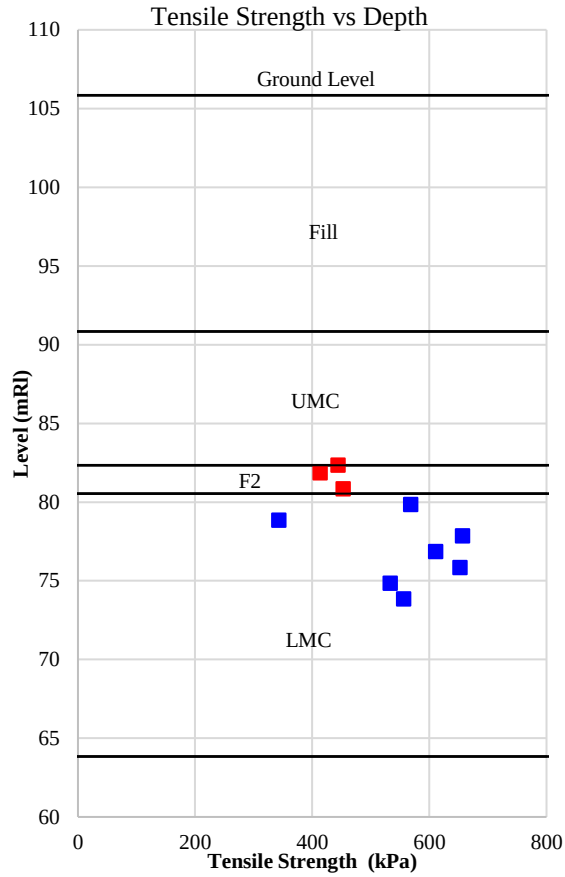

Figure 7. Tensile stresses vs depth.

4 DISCUSSION OF RESULTS USING NUMERICAL ANALYSIS

The above results of tensile strength are used in a numerical analysis with and without the use of tensile strength in the ground improvement. In figure 8 it is presented the cross section of a TBM shaft excavation in Kallang formation where GI has been used below the formation level.

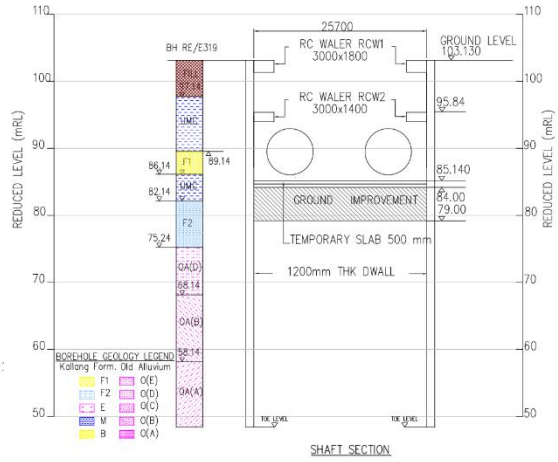

Figure 8. Cross section of the TBM launching shaft with geo profile.

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%. Tables 3 below shows the geotechnical parameters used during design.

For the ground improvement below formation level a compressive UCS strength of 1.6 MPA (Cu = 800 kPA) has been used and a stiffness Eu of 280 Mpa has been used. These parameters where defined by using experience of previous projects in similar ground conditions in Singapore.

The excavation sequence is a typical bottom up construction with casting of capping and waler beam while excavating.

Two numerical analysis results are showed, one without the use of tensile strenght in the GI (Analysis 1) and the second using 300 kPA tensile strength, this value is conservative considering the results of the section 3 tests.

Table 3. Geotechnical parameters of Kallang formation and Old Alluvium

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

* Note = Z denotes the depth in reduced level.

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

4.1 Discussion Numerical Analysis results

Two numerical analysis are compared in this section. In general the overall behaviour (displacements) of the excavation is the same for both cases, a tyipical mesh deformation is presented in the figure below

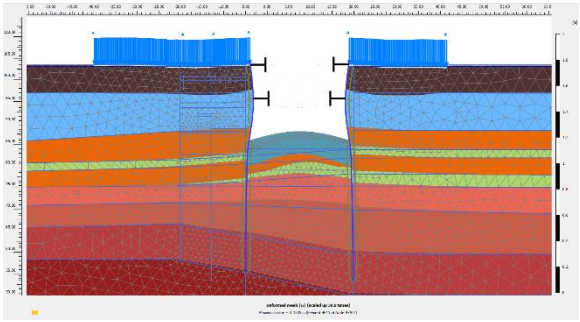

Figure 9. Mesh deformation when excavation to formation level occurs.

The figure above shows that the layer of ground improvement below the formation level reacts as with a "beam type" behaviour. This mean that in general the top of ground improvement layer shows tensile behaviour with the generation of cracks, the below figure shows the εxx deformation for the analysis 1.

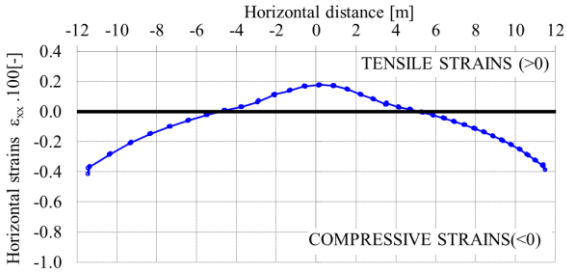

Figure 10. Horizontal strains in the top of the ground improvement block with 5 meters of GI thickness.

The figure below shows the development of failure points (shearing and tension) in the ground improvment block for Analysis 1 and Analysis 2 in the left and right respectively. It is clear that, adding tensile strength reducI think so es to (close to) zero the tension failure points.

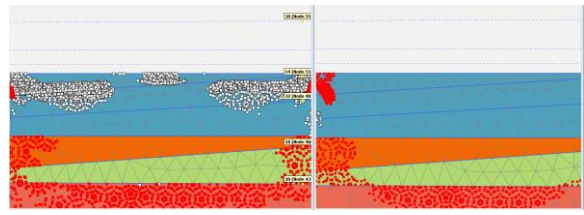

Figure 9. Failure points for Analysis 1 (left) and Analysis 2 (right)

In common practice in Singapore, no tension forces are allowed, however the above figure shows that by adding tension resistance, no failure (or little failure) is obtained. This is important, as the result of the criteria of using no tension resistance in general leads to increase thickness of ground improvement thereby increasing the cost deep excavation by increasing the ground improvement volume.

5 CONCLUSIONS

Deep excavations in soft ground often require additional stabilization through ground improvement (GI). Some of the common methods to improve the ground are Jet Grouting Piles (JGP), Deep Soil Mixing (DSM) or Wet Speed Mixing (WSM). JGP, DSM and WSM are achieved by mixing the soil with cement and water, generating a structure that performs well under compression forces but not under tension forces

In this paper it has been showed, through laboratory tests the results of tensile strenght of DSM samples obtained in Singapore. The results obtained were later used to highlight the importance of this parameter in design.

The author believes that more research is needed in this area, however, significant costs/time and construction program saving could be achieved by considering the tensile strength resistance in GI.

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