Evaluating the performance of jet grouting for reinforcement of port structure

2011 Pan-Am CGS Geotechnical Conference

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ABSTRACT
In order to assess the performance of jet grouting for reinforcement of port structure, a pile sheet pier with two levels of anchorage and initial water depth of 8m was modeled when submitted to dredging up to 6m deep and increments of the backyard load up to 60kPa. The stability of the structure with and without reinforcement was analyzed by limit equilibrium and finite element computational methods. The site of study is the region of Navegantes port, South Brazil, which consists of thick layers of fluvio-marine soft clay deposits, and represents the situation found in many port areas of the country.

RÉSUMÉ
Afin d'évaluer la performance du jet grouting pour le renforcement de la structure d'un port, un quai de planches à deux niveaux d'ancrage et avec une profondeur initiale de l'eau de 8m a été modélisé lorsqu'il est soumis à l'approfondissement jusqu'à 6m et les augmentations de la charge à l'arrière jusqu'à à 60 kPa. La stabilité de la structure avec et sans renforcement a été analysé par équilibre limite et des méthodes de calcul par éléments finis. Le site d'étude est la région du port de Navegantes, sud du Brésil, qui se compose par d'épaisses couches dês argiles mous fluvio-marines, et qui représente la situation typique des zones portuaires du pays.

1 INTRODUCTION

The occupancy of the berths of some Brazilian ports reaches values much higher than the 50%, which is the limit in order to avoid waiting time. The Container Terminal of the Port of Paranaguá, for example, located at Brazilian South, which accounts for 8% of container handling of port terminals in Brazil, has occupancy of berths of more than 90%, resulting in waiting time of up to 20 hours. The need for investment in port infrastructure in Brazil is due to the development of the country infra-structure among many other aspects, and the strengthening and improvement of existing berths are an excellent alternative in order to increase the cargo handling capacity of the Brazilian ports.

In Brazil, the technique of jet grouting has been used in order to improve the retaining structures of old port facilities. However, the increasing use of this technique without sufficient studies has raised doubts about its suitability in certain situations.

Although usually the jet grouting method is applicable in any type of soil, it appears that, depending on the strength and type of soil, there is a range of application of this soil treatment, due primarily to the costs of the method.

Using the geotechnical setting of the port of Navegantes, situated at South Brazil, the stability of a pile sheet pier with two levels of anchorage and initial water depth of 8m was analyzed. Based on the initial situation of the wall and simulating an improvement of the port facilities, twelve different scenarios were modeled, a total of 63 analyses. For each scenario it was stipulated an increase in workload and an increase in water depth, and by means of computer analysis they were compared with and without reinforcement.

2 JET GROUTING TECHNIQUE ON SOFT SOILS

The executive process of soil improvement with jet grouting can be roughly divided into three distinct phases: cutting, mixing and cementation. In the cutting phase of the soil structure is broken by horizontal jets of cement grout, water and / or air, dispersing the soil particles. The injection systems are three: in the single system only the cement grout is injected; with the double system the air is also injected with the grout and in the triple system it is necessary one nozzle for water and air and another for the grout.

The strength, deformability, permeability, the geometry of the soil treated and the treatment efficiency of a jet grouting are directly correlated with the characteristics of the executive process. These characteristics are modified according to the system used and are basically the following: flow and pressure of the fluids involved in the process (cement grout, water and air), diameters and number of injection nozzles, and rotation speed of the injector and water / cement ratio. Table 1 shows typical range of values of parameters and characteristics of the process. It can be seen that there is a wide range of values involved in the execution process, which explains the wide range of values of soil parameters of the soil treated.

The grouting technique development comes mostly from the practice on different types of soils and also from different systems and characteristics. Carreto (2000) shows that the application of jet grouting with a single system becomes inefficient and very expensive if applied on sandy soils with N_{SPT} values higher than 20 or in cohesive soils with N_{SPT} values higher than 5. As for the double system it is not usually used on cohesive soils with N_{SPT} values higher than 20. According to Kutzner

(1996), cohesive soils with undrained strength of 40 kPa and liquid limit of 40% are the limits for application of jet grouting.

Table 1. Typical characteristics of the jet grouting systems.

Characteristics / Systems		Single	Double	Triple
Pressure	Cement grout (MPa)	20 a 60	20 to 55	0.5 to 27.6
	Air (MPa)	-	0.7 to 1.7	0.5 to 1.7
	Water (MPa)	****	****	20 to 60
Flow	Cement grout (l/min)	30 a 180	60 to 150	60 to 250
	Air (m^3/min)	-	1 to 9.8	0.33 to 6
	Water (l/min)	****	****	30 to 150
Injector diameter	Cement grout (mm)	1.2 a 5	2.4 to 3.4	2 to 8
	Water (mm)	****	****	1 to 3
Number of injector nozzles	Cement grout	1 a 6	1 to 2	1
	Water	****	****	1 to 2
Water cement ratio		1:0.5 to 1:1.25	1:0.5 to 1:1.25	1:0.5 to 1:1.25
Ascent rate of the injector (m/min)		0.1 to 0.8	0.07 to 0.3	0.04 to 0.50
Rotation speed of the injector (rpm)		6 to 30	6 to 30	3 to 20

Guatteri et al. (2004) presented a case of application of jet grouting in marine clay at Southeast Brazil, for the deployment of tanks of a sewage treatment plant. In this type of soil there was a delay or reduction of the strengthening of the mixture cement/soil. This phenomenon, according to Abramento et al. (1998), is associated with the presence of organic peat soil, high moisture, low pH and high aggressiveness of the clay. The solution to the problem could be re-injecting, which could be very expensive.

Jaritngam (2001) presented a case of application of jet grouting as temporary retaining wall in a deep excavation for construction of a residential building located in Thailand. The soft clay deposit (undrained resistance, S_u = 20kPa) of about 15m thickness, was followed by a medium clay of 25m thickness and a layer of sand until the impenetrable to percussion. The analysis was carried out using FEM and limit equilibrium method for assessing the performance of jet grouting, considering the solutions with and without jet grouting. The maximum displacement of the wall was of 203mm for the situation without jet grouting, while the situation with jet grouting a displacement of 112mm was obtained. Without jet grouting, the safety factor was below 1.2, but with the treatment it was higher. However, it seems that the in situ measured displacements of the wall were much lower than those obtained in the modeling. This difference was attributed to high compressive strength of the treated material, which was not adopted in modeling.

3 SITE CHARACTERISTICS

3.1 Stratigraphy

At Navegantes site, field tests and laboratory were carried out: 103 standard penetration tests, 9 vane tests, 9 characterization tests, 41 triaxial UU, 3 triaxial CID and 15 consolidation tests. Results of these tests are presented elsewhere (Marques and Lacerda, 2002).

Although the stratigraphy of the site is variable, the deposit is typically formed by three distinct layers of clay, interspersed with fine and coarse sand as shown in Figure 1.

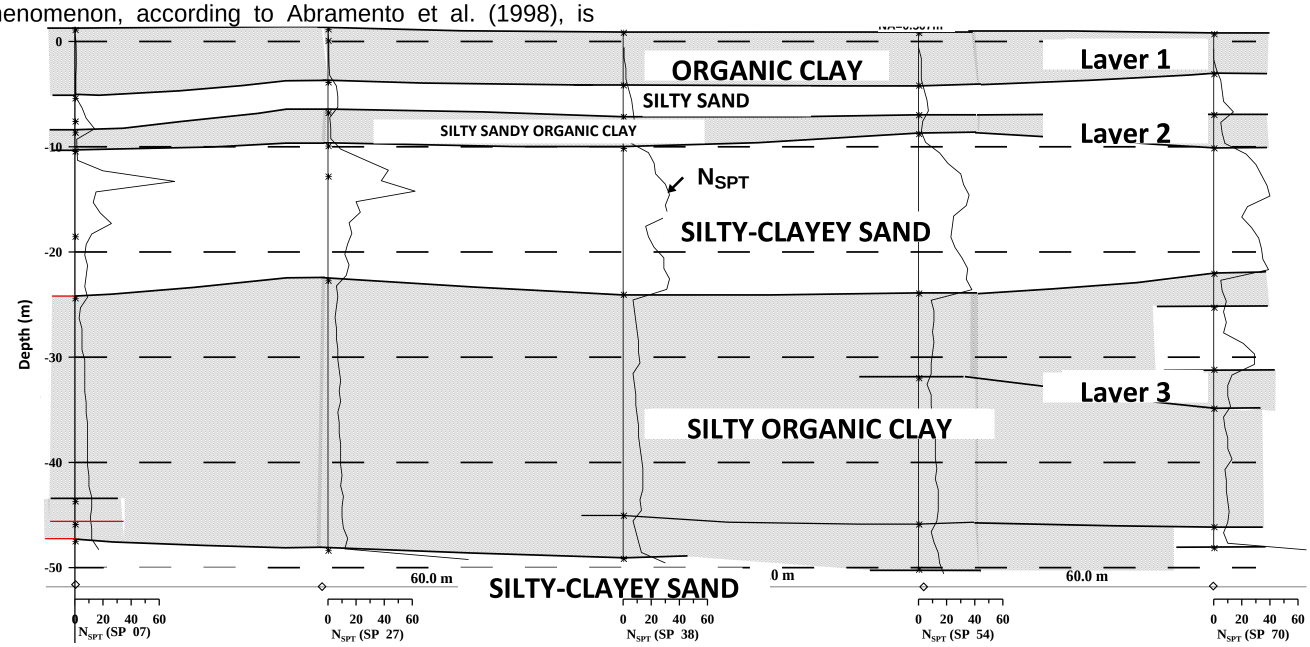


Figure 1. Typical geotechnical profile of Navegantes site (Marques and Lacerda, 2002).

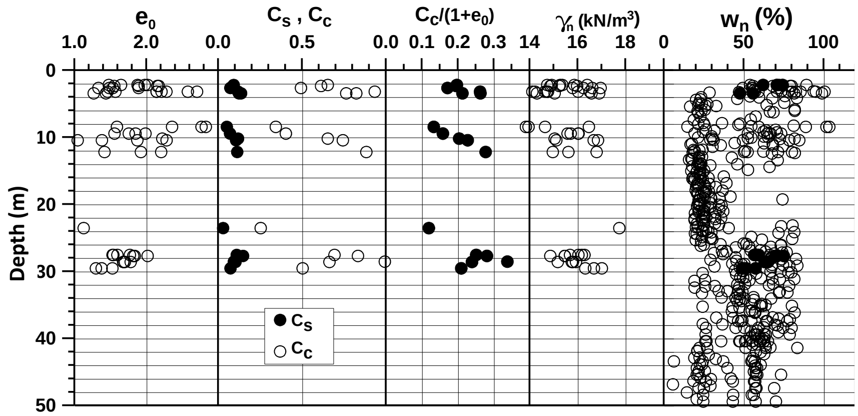


Figure 2. Typical geotechnical parameters of Navegantes site (Marques and Lacerda, 2002).

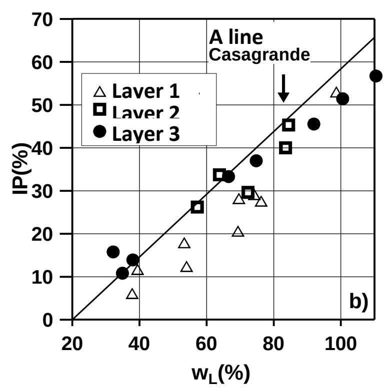


Figure 3. Casagrande chart.

In a few locations there may be a layer of sand at the surface, which could be due to dredged material or original mangrove material. The water table is shallow, normally located at the top of the surface clay layer (layer 1), which presents N_{SPT} <1 and thickness ranging up to 7m. Underlying the first layer is generally a layer of sand, then another layer of very soft clay to soft, layer 2, with thickness up to 10m.

At the deepest layer of clay, layer 3, the average consistency is hard, but sometimes soft clay is present for the first 2 to 12m. Its total thickness ranges from 13m to 32m with top from 16.5m to 38m deep. There were indications of the occurrence of organic matter down to layer 3.

3.2 Site soil parameters

The soft clay at the site is very compressible, although the initial void ratio (e_0) and the initial natural water content (w_n) are well below those of some Brazilian marine clays, such as Sarapuí, which features high e_0 decreasing from 4.9 to 2.5 with depth (Almeida and Marques, 2003). As shown in Figure 3, the soft clay soil of all the 3 layers is very plastic, but the IP and compressibility of this clay is also lower when compared with some coastal Brazilian clays (Almeida et al. 2008), due to its high content of silt and sand. The characteristics and parameters range of the soft clay layers of Navegantes site are presented at Table 2.

Table 2 Soil parameters and characteristics of soft clay layers

Soil characteristics	Layer 1	Layer 2	Layer 3
Depth of the top (m)	0 - 7	6 - 16,5	16,5 - 38
Thickness (m)	0 - 7	0 - 10	13 - 32
N_{SPT}	0 - 5	0 - 8	4 - 35
C_c	0,18 - 0,93	0,34 - 0,88	0,25 - 0,99
C_c / (1+ e_0)	0,09 - 0,26	0,13 - 0,27	0,11 - 0,37
w_n (%)	47 - 100	49 - 103	40 - 75
w_L (%)	40 - 98	32 - 110	57 - 84
IP	6 - 53	11 - 57	26 - 46
γ_n (kN/m^3)	14 - 17	13,8 - 16,8	14,8 - 17,7
e_0	1,26 - 2,70	1,37 - 2,82	1,12 - 2,01
c_v (10^{-8} m^2/s)	2,4 - 81	2 - 49	2,7 - 17
S_u (kPa)	3 - 20	30 - 60	>60

4 SOIL PARAMENTERS AFTER TREATMENT

In the proposed methodology, the jet grouting is modeled with new properties after the soil treatment. Thus a column of jet grouting does not have the same characteristics from top to bottom, as the element's properties depend on the soil of origin, meaning an optimized design, since the low resistance values obtained in layers where the jet grouting is less efficient are restricted to these layers.

Thus, for the modeling of the solution, it is necessary to know the geometry and the new properties of the soil after treatment. The ideal condition for this is to perform tests with columns, collecting samples of the treated material, obtained during the execution of the columns, and test samples taken directly from the column after completion of treatment, at various depths and with different ages. However, when designing with jet grouting, these procedures cannot be adopted in advance. The common practice is to set previously the geometry and strength parameters, so that later, during the execution of the jet grouting, these would be attained by controlling the conditions shown in Table 1, thus relying on the constructor experience.

It is therefore very important that the soil parameters and variables considered after soil treatment when designing are in accordance with the stratigraphy, soil characteristics, the procedures used, and equipment available to perform the services.

4.1 Soil strength

The parameters of the material treated with jet grouting used for the modeling were based in correlations presented in literature, as shown in Table 3. The injection pressure, ascent rate and speed rotation of the injector and water / cement ratio of the cement grout interfere directly in the shear strength final value. This is due to the fact that the larger the volume of cement in the material treated, the greater the resistance. That is, in a treatment process, without changing the diameter, the value of the strength could be increased by modifying only the speed and the water / cement ratio.

The water / cement ratio used in the treatments vary between 0.8 and 1.5. The type of soil treated and the water / cement ratio used in the composition are the factors that most influence the final compressive strength (Kutzner, 1996).

Since the presence of water in the soil cement mixture, as well as concrete in general, decreases the final value of resistance, the higher water content of the natural soil, as those observed in clayey soils, leads to lower values of resistance. The clayey soils will also present lower values of resistance when compared with sandy soils, even when they present the same N_{SPT} value.

Table 3 also shows typical values of cohesion, c, directly correlated with the compressive strength (σ_c), not taking into account the different injection systems.

4.2 Permeability

The permeability of the material treated with jet grouting is very low, the order of 10^{-8} to 10^{-9} m/s (JJGA, 1995). According to Kutzner (1996) the values of permeability of soil treated with jet grouting are hardly more than 10^{-8} m/s and can reach values of about 10^{-11} m/s in clayey soils.

4.3 Specific gravity

Kutzner (1996) points out that the water / cement ratio of the grout and the void ratio of the original soil are directly related to the final value of specific gravity, which is in the range of 18 to 21 kN/m^3.

4.4 Poisson's ratio

The Poisson's ratio in the undrained condition is $\nu_u = 0.5$, which satisfies the initial condition of the soil before treatment. However, in computational analysis often this ideal condition leads to divergence, since the water is not strictly incompressible. For this reason it is often used for computational modeling $\nu_u = 0.495$, thus considering the soil mass slightly compressible. After the treatment the Poisson's ratio of the column is $\nu = 0.2$, which is the value usually employed for concrete. Although tests to obtain this parameter are not usually carried out, the variability of the Poisson's ratio is small.

Table 3 Soil parameters and characteristics of soft clay layers.

Water cement ratio	Compression Shear Strength (MPa)				
	Organic clay	Clay	Silt	Sand	Ref.
-	-	1 to 5	1 to 5	5 to 11	Welsh and Burke (1991)
0.67	-	-	6 to 10	10 to 14	Bauman and Dupeuble (1984)
1.0	-	-	3 to 5	5 to 7	
-	-	1 to 5	1 to 5	8 to 10	Paviani (1989)
0.8 to 1.0	0.5 to 2.5	-	-	-	Teixeira et al. (1987)
0.8 to 1.2	-	1.5 to 3.5	2 to 4.5	-	
0.8 to 1.5	-	-		2.5 to 6	
0.96 to 1.08	0.3	1	-	1 to 3	JJGA (1995)
-	-	0.5 to 4	1.5 to 5	3 to 8	Guatteri et al. (1994)
-	0.14	-	-	-	Guaterri et al. (2004)
0.67 to 1.0	< 3	< 12	< 12	< 15	Kutzner (1996)
***c* /** Compression Shear Strength					
0.8 to 1.2	-	0.30	0.25	-	Teixeira et al. (1987)
0.8 to 1.5	-	-	-	0.19	
0.96 to 1.08	0.33	0.30	-	0.16 to 0.20	JJGA (1995)

4.5 Young's Modulus

The Young's Modulus of the treated material can be obtained by direct correlation with the compressive strength, but there is a wide range of values as shown in Table 4.

The analysis of the values shown in Table 4 doesn't lead to a direct relationship between the size of the original material and the values of the correlation E/σ_c, since both the Young's Modulus and compressive strength are influenced by the soil granulometry, and both were greater in sandy soils and lower in clay soils. It is precisely for this reason that the JJGA (1995) recommends a unique relationship to all soil types.

Table 4 Relationship between Young's Modulus and compression shear strength (σ_c).

Soil type	E / σ_c	Reference
All soil types	100	JJGA (1995)
Fine to medium sand	360	Lunardi et al. (1986)
Peat	600	Paoli et al. (1989)
Silty clay ("Massapê" soil)	700	Novatecna (1994)
Gravel with sand	900	Lunardi et al. (1986)
Silty clay ("Massapê" soil)	2000	Novatecna (1994) (considering 40% of the limit load)

4.6 Soil parameters used for the models

Table 5 shows the soil parameters used for the analysis, before and after the treatment. The main geotechnical parameters required as input data for FEM analysis are: ϕ',c', E, ν, γ_{sat}, γ_d, K_0, k_x and k_y.

The coefficient of earth pressure at rest (K_0) was estimated for a clay effective friction angle of 25° (K_0 = 0.577).

5 LIMIT EQUILIBRIUM ANALYSIS

Analysis by the method of limit equilibrium consists in a research of the mechanism of collapse, resulting in the lower safety factor associated. This is an approximate calculation method but which has led to solutions that are consistent with the actual cases observed in the field. In this paper it was used the program SLOPE-W to obtain safety factors associated with the set of scenarios (Fig. 4). Two surfaces of rupture were analyzed: global stability and the pullout of the anchors (local failure), as shown in Figure 5. The global rupture surface is circular and it must necessarily pass by the bottom of the wall, and the local rupture surface is purposely passing by the foot of the slope (point A). In the case of local rupture, the passive earth pressure (E_p) must be introduced manually, estimated after Mohr-Coulomb equations, considering the depth of the wall.

The stability analysis of the solution of reinforcement with jet grouting can be accomplished using the methodology presented, simulating the jet grouting as a layer of soil behind the wall. However, for the analysis of the local rupture, it must be considered the wall and the reinforcement working together as a rigid structure. It means that an analysis of the rupture surface must be considered, without jet grouting, but with a load at point A, related to the passive earth pressure along the length of the jet grouting, not only the length of the old wall.

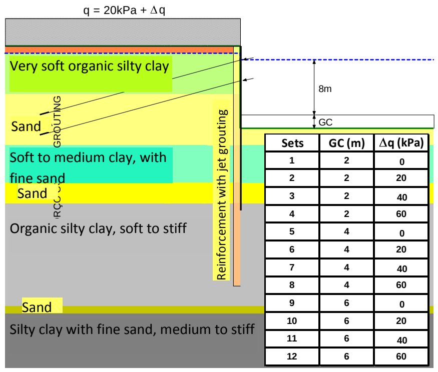
The analysis of the global failure surface gives an overall safety factor very close to the real situation. However, for the local analysis, the E_p value that should be considered, especially in situations where the length of the wall is bigger (for example with the jet grouting), the equations of Mohr-Coulomb can lead to very high values of E_p, which in practice cannot occur because it would mean extremely high deformations (Oliveira, 2010).

The jet grouting provided a direct gain in safety factor when analyzing the global rupture. Purposely the total depth of treatment was chosen so that the critical surface rupture did not pass in any case below the treatment, in order to better compare the performance of the solution. Thus, the small stretch of the critical surface that intercepts the treatment provides an increase of the resistance. This increase was sufficient for the problem of global stability to become less relevant, since in all cases the global safety factor was higher than 1.25, when reinforced (Fig. 6a).

Table 5 Soil parameters of natural soils and after soil treatment.

Layer	Thickness (m)	Parameters of natural soil					Parameters after soil treatment					
		γ_{nat} (kN/m³)	ϕ (°) *	c' - S_u (kPa)*	E_d - E_u (kPa)*	ν' - ν_u *	σ_c (kPa)	γ_{jet} (kN/m³)	ϕ	c_{jet} (kPa)	E_{jet} (kPa)	ν_{jet}
Sandy fill	1	18	30	0	25000	0,3	2500	22	30	722	500000	0.2
Very soft silty organic clay	6	15.5	0	10	5000	0,49	500	22	0	250	100000	0.2
Sand	7.5	17	32	0	25000	0,3	2500	22	32	693	500000	0.2
Very soft to medium clay with fine sand	5.5	15.3	0	45	22500	0,49	1500	22	0	750	300000	0.2
Sand	3	17.2	32	0	35000	0,3	2500	22	32	693	500000	0.2
Very soft to stiff organic clay	15	15.8	0	60	30000	0,49	3000	22	0	1500	600000	0.2
Sand	1	17.5	35	0	45000	0,3	3000	22	35	781	600000	0.2
Medium to stiff silty clay with fine sand from	8	16.8	0	80	40000	0,49	3000	22	0	1500	600000	0.2

*Granular soils – effective parameters; clayey soils – undrained parameters.



Sets	GC (m)	Δq (kPa)
1	2	0
2	2	20
3	2	40
4	2	60
5	4	0
6	4	20
7	4	40
8	4	60
9	6	0
10	6	20
11	6	40
12	6	60

Figure 4. Geotechnical models and sets.

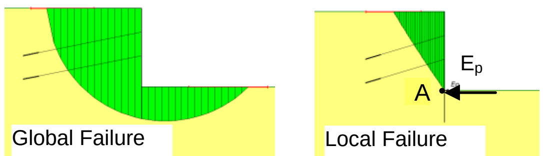


Figure 5. Rupture surfaces - limit equilibrium analysis.

It is important to note that for this type of global analysis the jet grouting is effective only up to the depth where the critical surface is intercepting it, thus, the importance of the determination of the strength parameters of the treated soil in this region for this kind of analysis.

In the case of local analysis, the consideration of E_p values should be used carefully. The first point is to question the choice of the rotation point of the wall. When running the program, it is not possible to consider a rotation point of the wall below point A. An overview of the results showed that the higher the length of the wall, further from reality is the analysis. In the next chapter, it will be shown that the rotation point of the wall is better defined from FEM results.

For the local analysis, in order to evaluate the range of earth pressures, it was calculated a mobilized earth pressure (E_m) considering SF = 1. Then, an available earth pressure (E_{disp}), due to the length of the wall, was calculated also. The limits for E_{disp} will be E_p and E_0 (earth pressure at rest). The SF obtained for these limits are shown in Fig. 6b, for all sets described in Figure 4.

The second important point of the local analysis by the limit equilibrium method is to assess what amount of earth pressure should be used. Considering the situation as the limit for the rupture, the earth pressure to be considered should be the passive earth pressure, E_p, however, this assumption can lead to very high displacements, which are not compatible with the performance of the jet grouting and the wall. The value of the earth pressure to be considered should be the between E_p and E_0, as shown in Figure 6.

Independently of some misleading by the limit equilibrium analysis, it showed that the jet grouting provides an improvement on safety directly proportional to the additional length of the wall. The hypothesis of a failure surface that would pass through the treatment with jet grouting is a hypothesis that can be discarded, since the strength of the material treated with jet grouting is well above the original soil.

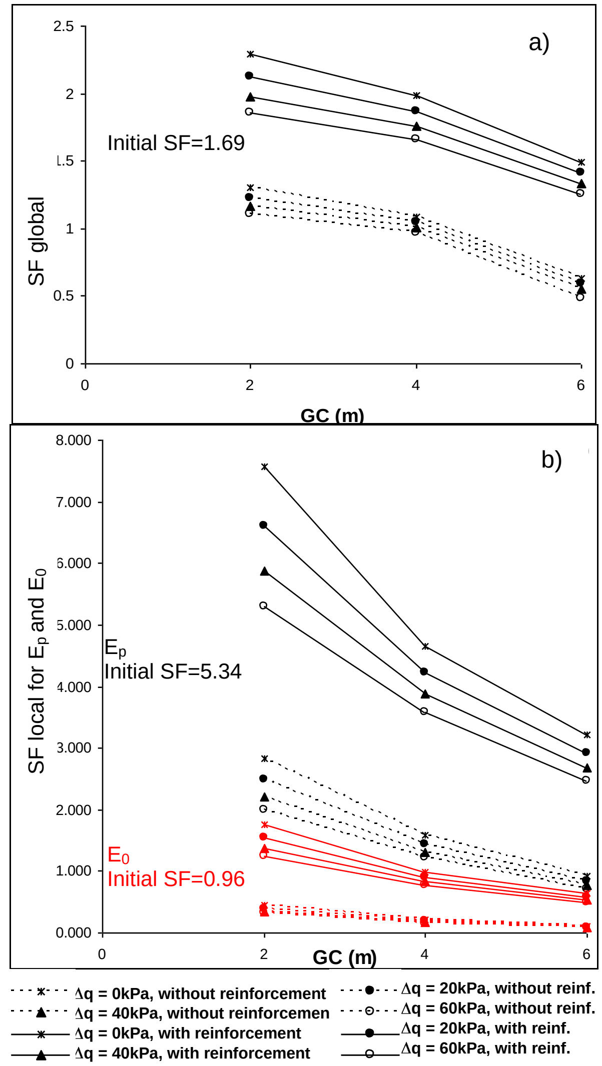


Figure 6. Safety factor variation with dredging depth (GC) for: (a) global rupture (b) local rupture.

6 FINIT ELEMENT ANALYSIS

The analysis by the method of limit equilibrium, due to its limitations, provided only an initial notion about the behavior of the problem and can be viewed as a first step to be taken before more sophisticated analysis. In order to better understand the behavior of the soil before and after the treatment, the twelve scenarios (Fig. 4) were modeled by FEM, using the program Plaxis. The program simulate the evolution of the dredging and the surcharging (Δq) from an initial scenario, and it can suppress and / or change the properties of regions previously established for the soil layers or treatment, and can change the values of surcharge

Figure 7 shows the mesh used for modeling the initial situation in the already deformed condition, and the set 6 with and without surcharge. The deformations calculated for the various set of scenarios show clearly the effectiveness of treatment with jet grouting. The deformations obtained were always significantly lower with treatment.

Comparing the yielding of the soil mass shown in Figure 7 with the situations after the increase of depth of the dredging and surcharge, both for the situation with and without reinforcement there is a considerable increase of yielding points. However, with the jet grouting these additional points of plastification inside the mass of soil are lower, and there is not any yielding of the soil treated with the jet grouting.

Given the importance of the stiffness parameters of the treated material, it is clear that for this kind of analysis it is more important to determine parameters of deformability of the treated material, such as E and ν than compressive strength of the soils that received treatment.

The scenarios until the collapse were strategically chosen in order to better evaluate of the performance of the solution. In situations without reinforcement the collapse occurred for scenarios 8, 11 and 12. The scenario 12 with reinforcement also showed collapse of the soil mass. The four cases of collapse are shown in the Figure 8 by lines of "failures". These results are only illustrative, since they represent an interruption in the calculation. However, for some scenarios, the error in the analysis did not occur, resulting in excessive displacements, which in practice can be considered as collapse. This is the case for all scenarios with a surcharge of 80kPa, even with reinforcement, and also for scenarios with a surcharge of 60 kPa, which also showed excessive displacements for the cases without reinforcement.

It is observed by these graphs that the movement to which the structure will collapse corresponds to what was called local analysis in the limit equilibrium method. It appears that the pre-stressing of the tie rods from a given time, is overcome by the efforts of earth pressure and the wall collapses with the largest deformation occurring at the top of the wall.

The magnitude of bending moments appears to increase from the initial situation (Figure 9), however less pronounced in cases with reinforcement. However, these increases could be easily absorbed by the metal profiles of the wall. In works of this kind, where the structural elements are usually robust, the focus of the analysis is on the geotechnical stability of the contention.

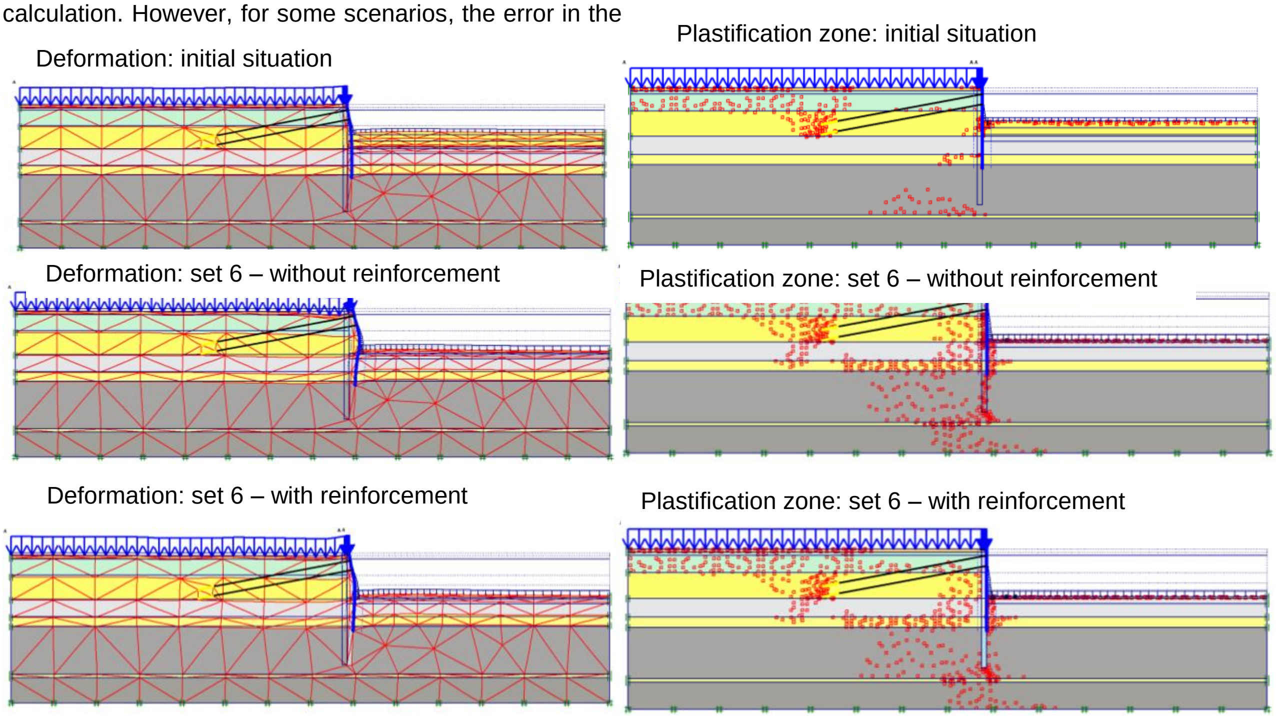


Figure 7. FEM analysis: deformation and plastification: initial condition, set 6 without and with reinforcement.

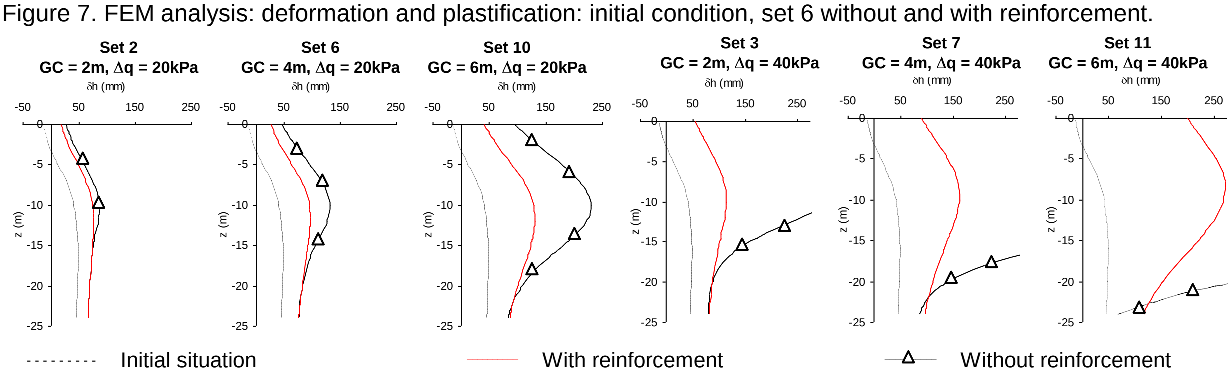


Figure 8. Horizontal displacements from FEM analysis.

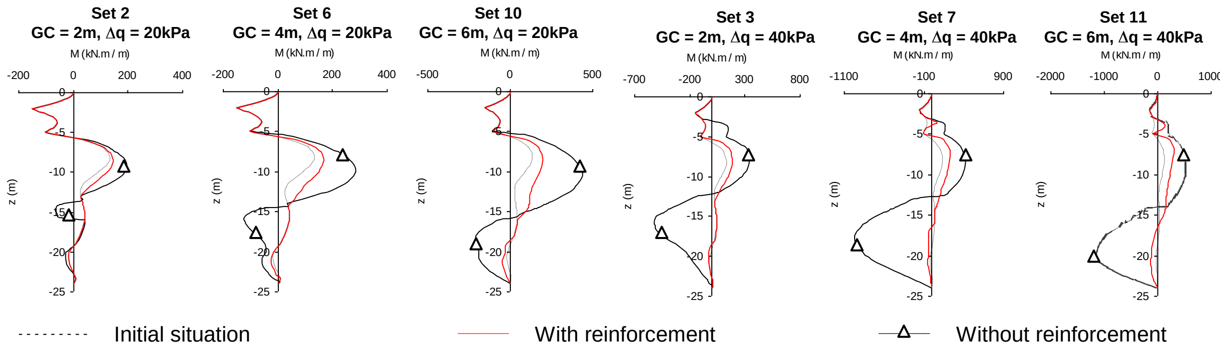


Figure 9. Bending Moments from FEM analysis.

7 CONCLUSIONS

The jet grouting method for treatment of soil for port areas is effective, and although these regions in Brazil present layers of soft soils, it does not seem to be a limitation for this kind of solution.

The FEM analysis seems to be more suitable to simulate the scenarios, since with the limit equilibrium analysis does not evaluate the deformations of the structure.

Some recommendations when using jet grouting on organic soft soils:

-the mix of soil and cement should be subjected to physical and chemical characterization, and laboratory tests of strength;

-during the execution of jet grouting it is suggested to run the column tests, with technological control of soil-cement material obtained from the reflux, which could be compared with samples collected directly from intact columns;

-in the final phases of the work itself, if excavation work is planned, it is suggested a calibration of the parameters for the implementation of the columns for a back analysis, and the withdrawal of samples for monitoring and verification of the design.

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