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Static Analysis of Retention Elements Using Piles and Shotcrete

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Abstract. Slope stabilization by the installation of piles is one of the innovative slope reinforcement techniques that have been introduced in recent years. This paper shows the analysis of static behavior against lateral load of a slope by using a tridimensional numerical modeling software of finite differences, considering both the influence of the excavation and the soil-pile interaction, analyzing the elastic-plastic deformations by using Mohr-Coulomb criteria. This paper also shows that the horizontal displacements and factor of safety are affected by the geometry and position of the pile.

Keywords. Numerical modelling, pile wall retaining, shotcrete, retention elements.

1. Introduction

Soil retention structures are frequently used in engineering projects, such as pile retaining walls, bridge abutments, propped walls, underground walls, among others. There are different types of retaining walls which can be classified as follows:

- Bored piles retaining wall: Tangent piles wall, Secant piles wall, Contiguous piles wall. (Figure 1),
- Soldier piles and lagging: Steel beams (H section profiles), Steel beams (Circular section profiles), Caissons and Bored cast in-situ concrete piles. (Figure 2).

The Berlin wall, a type of soldier pile wall, is distinguished by having prefabricated panels (mainly wooden planks or concrete panels) placed horizontally or lagging made in situ such as shotcrete with electro-welded mesh [1].

The lateral support of soils and the complex calculations that can occur during the design of retaining walls, are an important factor in the design of retention structures, the most appropriate way to analyze this behavior is by means of finite difference calculations where the models are incorporated to simulate the soil behavior and soil structure interaction. For this reason, it is necessary to study more thoroughly the static behavior of this type of retention structures, to have a better understanding of the phenomenon and with that improve the currently available design methods. The models

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developed consider the dimensions of the pile wall, the properties of the soil, and the depth of embedment.

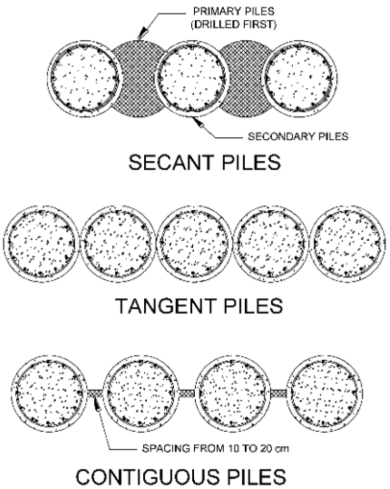

Figure 1. Bored piles retaining wall [2].

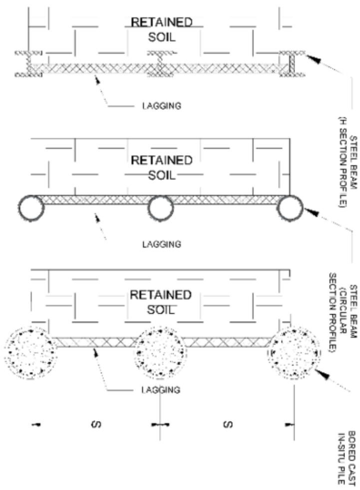

Figure 2. Soldier pile walls.

2. Justification

Nowadays, the need to build retaining walls that present greater height, shorter construction time, lower costs and less work area, leads us to look for new techniques and construction technologies.

An adequate design of this type of structure depends mainly on a correct estimation of the form and magnitude of the expected displacements. This determines the distribution of lateral earth pressure [3], which is related to some other factors, including the drainage conditions and parameters of shear strength.

The finite differences method is a general numerical method for the approximation of solutions of partial differential equations normally used in diverse problems of engineering and physics, it is developed to be used in computers and allows the solution of differential equations associated with a physical problem on complex geometries.

3. Description of the research site

A highway 9.5 km long is to be built in the West region of Mexico City and a bit more than 1 km is underground, located on *Zona de Lomas*, as described by the Mexico City building code.

From the geological point of view, the project is located within the Tarango formation, mainly characterized by tuffs, breccia and pyroclastic materials, interbedded by alluvial sands. In this region it is common to find caverns associated with rock extraction for construction. The oldest deposits of the Tarango formation are composed of yellow tuffs that in some regions reach thicknesses greater than 50 meters. In general, the tuffs found in this area are strongly cemented and have compactness ranging from dense to very dense, presenting considerable resistance to shear stress and low compressibility.

A solution of concrete piles and shotcrete as a retaining system was proposed for the section under research, which will allow to maintain a fluid traffic in the depressed area.

In general, in the stratigraphic sequence found on this site, four different units can be distinguished in the following order: upper alluvial sequence, cemented tuff, lower alluvial sequence and Tarango formation [4].

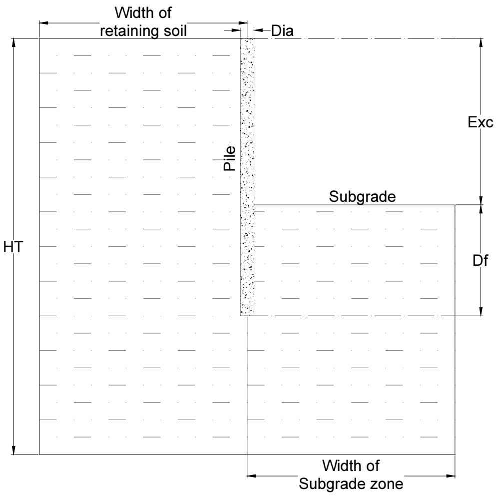

Figure 3. Proposed retaining wall and nomenclature.

4. Numerical modeling of the retention wall

4.1. Parameters and characteristics of the model

To reduce the geometry of the problem mentioned within this article, a structure adjusted to the geometrical specifications of the project is established below. The objective is to define a section that satisfies the security criteria, but optimizing the resources.

Table 1. Resume of soil properties (Geotechnical model).

From (m)	To (m)	Thickness (m)	c (kPa)	φ (°)	γ (kN/m³)	Description
0.00	1.20	1.20	10	20	16.50	Fill layer. Light brown sandy material with gravel.
1.20	8.40	7.20	14	21	17.90	Light brown silty sand with some gravel of high compactness.
8.40	10.00	1.60	16	28	16.50	Light brown pumice sand of medium-high compactness
10.00	18.70	8.70	16	30	17.30	Light brown sandy silt of hard consistency
18.70	30.00	11.30	20	40	18.00	Light brown sand with gravel of very high compactness (Tarango Formation)

In Figure 3 is shown the geometry proposed for the model, where "Dia" is the diameter of the pile, "Exc" is the depth of the excavation, "Df" is the embedment depth of the pile, "Ht" is the total height considered for the numerical model.

The fixed project data are as follows: the depth of the excavation is 9.00 m, the width of the road is 8.00 m (zone in depressed) and finally the resistance to compression of concrete for the piles (f'c) is 25 MPa.

For this research, some variable values were proposed for the model geometry. These variables entail the diameter, embedment depth and pile spacing [5]. Soils properties of the geotechnical model are shown in Table 1.

The proposed diameters for the piles are: 0.80 m, 1.00 m and 1.20 m. The depth of embedment is in function of the depth of the excavation, that is 0.4, 0.5 and 0.6 times the depth of the excavation. The separation between piles is a function of the piles diameter; the values are 2, 3 and 4 times the diameter of the pile.

Based on the number of variables to be used, the number of built models according to the combinations were 27 models (Table 2).

Table 2. Proposed geometry of the models.

Numerical Model	Depth embedment (m)	Pile diameter (m)	Distance between piles* (m)	Factor of Safety (Finite differences)
ERS4420	3.60	0.80	1.60	4.95
ERS4430	3.60	0.80	2.40	2.45
ERS4440	3.60	0.80	3.20	1.69
ERS4520	3.60	1.00	2.00	4.20
ERS4530	3.60	1.00	3.00	1.89
ERS4540	3.60	1.00	4.00	1.43
ERS4620	3.60	1.20	2.40	3.40
ERS4630	3.60	1.20	3.60	1.58
ERS4640	3.60	1.20	4.80	1.26
ERS5420	4.50	0.80	1.60	5.11
ERS5430	4.50	0.80	2.40	2.41
ERS5440	4.50	0.80	3.20	1.68
ERS5520	4.50	1.00	2.00	4.05
ERS5530	4.50	1.00	3.00	1.83
ERS5540	4.50	1.00	4.00	1.43
ERS5620	4.50	1.20	2.40	3.32
ERS5630	4.50	1.20	3.60	1.64
ERS5640	4.50	1.20	4.80	1.27
ERS6420	5.40	0.80	1.60	5.27
ERS6430	5.40	0.80	2.40	2.41
ERS6440	5.40	0.80	3.20	1.68
ERS6520	5.40	1.00	2.00	4.14
ERS6530	5.40	1.00	3.00	1.90
ERS6540	5.40	1.00	4.00	1.43
ERS6620	5.40	1.20	2.40	3.51
ERS6630	5.40	1.20	3.60	1.63
ERS6640	5.40	1.20	4.80	1.26

4.2. Development of the numerical model

Numerical model is composed of three-dimensional zones, with solid tetrahedral elements, both for modeling the ground and for modeling the piles. Among the three-dimensional elements with constant deformation, the tetrahedra have the advantage of not generating physically inadmissible deformation modes. However, when these are used in the terms of plasticity, they do not provide enough deformation modes. To overcome this problem, a mixed discretization process was applied. The generated three-dimensional model is shown in Figure 4.

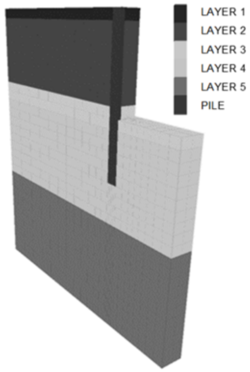

Figure 4. Perspective of the three-dimensional model of finite differences.

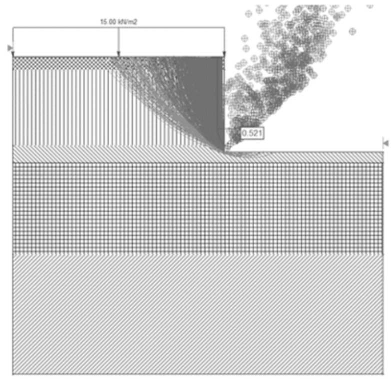

Figure 5. Slope stability considering Limit Equilibrium theory. Factor of Safety 0.521. Considering an overburden in the upper surface (15.0 kN/m2) and without shotcrete.

In the analysis, the state of geostatic stresses was initially determined, before and after the piles were installed, so that three stages of excavation were simulated, each -stage was 3.00 m deep, until reaching the total depth of excavation. Under these conditions, after each stage of excavation, the equilibrium of the system was resolved.

In the last stage, a surcharge of 15.0 kPa was applied on the upper surface of the model (natural ground level, elevation +0.00 m).

The system was analyzed without using shotcrete to observe the displacements of the soil between piles.

The behavior of the soil was simulated with an elastoplastic stress-strain relationship with a Mohr-Coulomb failure criterion, which was considered appropriate bearing in mind the low level of expected deformations due to the compacity of the soils found.

Table 3. Comparison of results from Finite Difference software and Limit equilibrium software.

		Maximum horizontal displacement (cm)	**Factor of Safety**
ERS4420	Finite Difference	4.77	4.95
	Limit equilibrium	5.01	2.90
ERS4430	Finite Difference	7.78	2.45
	Limit equilibrium	8.36	1.70
ERS5640	Finite Difference	6.09	1.27
	Limit equilibrium	31.32	1.13
ERS6420	Finite Difference	3.74	5.27
	Limit equilibrium	5.89	3.15
ERS6430	Finite Difference	5.13	2.41
	Limit equilibrium	9.58	1.70
ERS6620	Finite Difference	2.68	3.51
	Limit equilibrium	3.70	2.20
ERS6640	Finite Difference	5.27	1.26
	Limit equilibrium	9.77	1.10

4.3. Comparison of methods

Before compiling, synthesizing, graphing and analyzing the information for all the models, a reference or comparison criterion was sought with which to compare and above all assess the accuracy of the results obtained. Therefore, a retaining structure design software that works with the limit equilibrium method [1] was used, where the project data were entered applying the same geometric characteristics and geotechnical parameters, obtaining as a result, permissible factors of safety lower and displacements greater than those obtained by numerical modeling (Table 3).

5. Analysis and interpretation of results

To evaluate if the slope was unstable during the excavation stages as well as during the service time, a previous analysis was performed with a software using the Janbu's simplified method with the limit equilibrium theory, simulating the excavation stages without piles, considering the same geometrical and geotechnical characteristics, thus obtaining the behavior of the soil without piles and justifying the needing of a retaining wall, since the soil is unstable during and after the excavation as shown in Figure 5 where we can see the spectrum of factor of safety that they do not reach the equilibrium condition (FS $\geq$ 1).

Once the instability of the slope was determined, the analysis of the 27 models shown in Table 2 was carried out, calculating the factor of safety, plotting the displacements of the soil between piles (Figure 6), as well as that of the piles, in addition visualizing the soil failure mode and the plasticizing points of the model (Figure 7).

For purposes of this investigation, factors of safety between 2 and 4 were considered as permissible, to avoid working with oversized values (greater than 4).

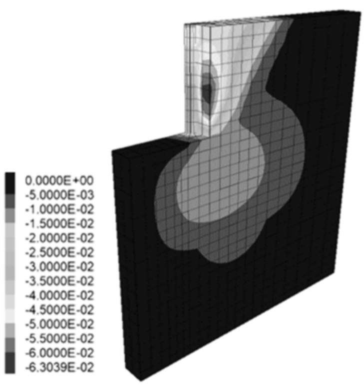

Figure 6. Horizontal displacements (meters) considering an overburden in the upper surface (15.0 kN/m^2) and without shotcrete.

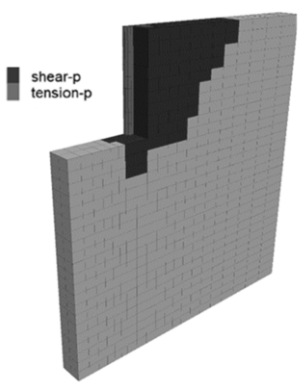

Figure 7. Plasticity state after excavation, considering an overburden in the upper surface (15.0 kN/m^2) and without shotcrete.

The effect of pile spacing on the factor of safety of the slopes is shown by the relationship of the factor of safety versus Sp/D ratio (Figure 8). The factor of safety of the slopes, as expected, decreases by increasing the pile spacing [5].

Otherwise, analyzing all the performed models in terms of displacements of the pile and the soil between the piles, the horizontal displacements in the head of the piles go from 2.7 cm for the most conservative horizontal displacement, to 10.0 cm for the most critical displacement; while for the soil between the piles the most critical horizontal displacement is 10.3 cm.

Once selected and analyzed, the models that are within the acceptable range of factors of safety, have horizontal displacements in the head of the piles that go from 2.7 cm corresponding to the more conservative horizontal displacement and 7.8 cm for the most critical, while for the soil between the piles the most critical horizontal displacement is 6.7 cm (Figure 9).

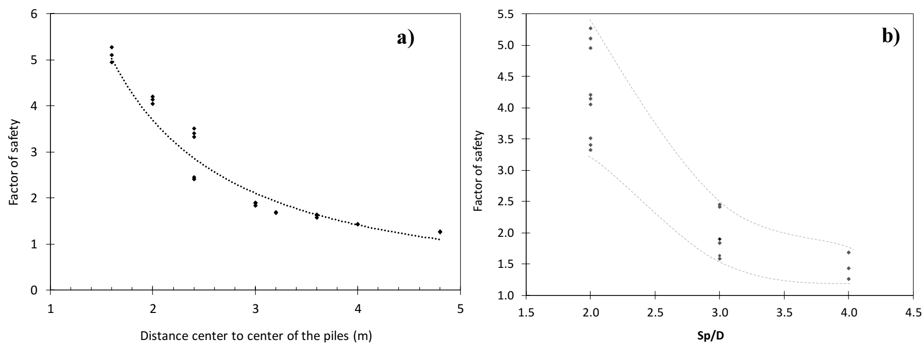

Figure 8. a) Effect of pile spacing. b) Effect of center to center pile spacing versus Diameter ratio (Sp/D).

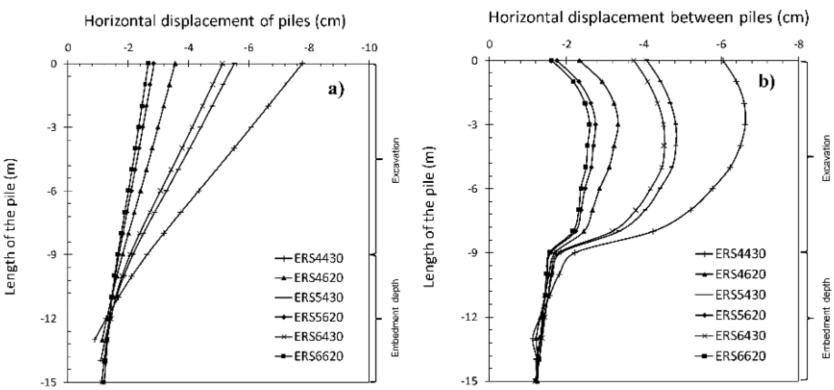

Figure 9. a) Horizontal pile displacements. b) Horizontal displacement of the soil between the piles. (Both for piles with a factor of safety between 2 and 4.

On the other hand, as illustrated in Figure 10 a single model that was performed without shotcrete and the displacement was registered and plotted, after this, the same model was performed again from the beginning, by simulating the excavation and setting a mesh that represents the shotcrete along the height of the wall.

6. Conclusions

Three-dimensional numerical models of finite differences were developed for the analysis of the retention system under static lateral loading conditions, considering the interaction between the pile and surrounding soil.

The importance of the geometry of the pile (the pile diameter, the depth of embedment and pile spacing) has been shown in this paper, that in collaboration with the properties of the soil, have a combined effect on the maximum driving force that the slope can transfer to the pile wall [6].

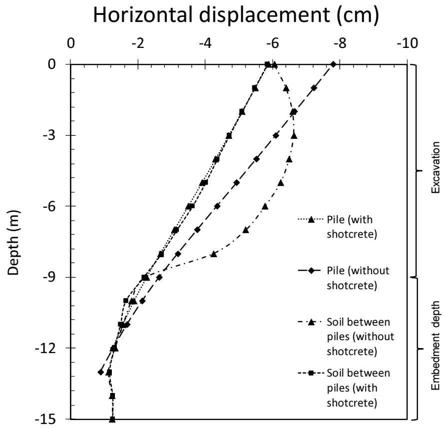

Figure 10. Effect of the use of shotcrete in a berlin pile wall (Model no. ERS4430).

The factor of safety of the slopes, as expected, is decreasing by increasing pile spacing or decreasing pile diameter or depth of embedment. It is showed the sensitivity of the model to changes in the pile geometry, mainly the pile spacing (Figure 8), the pile spacing is the most important geometric characteristic to modify the factor of safety; for this case, the optimal distance center to center is placed between 2.0 m and 3.0 m.

In addition the models without shotcrete were revised to compare the deformations of the soil between piles, it also demonstrates the importance of the shotcrete to reduce the horizontal displacements between piles (Figure 10), the constructive procedure in the analysis was taken into account (excavation steps).

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