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Deep Excavation in Redeposited Soils in Mining Areas

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Abstract. The Western region of Mexico City is known for having volcanic soil that is suitable for the exploitation of aggregate, which is useful in construction. This gave rise to mining regions where natural and man-made deposits were subsequently made; nowadays this land is for building modern structures. In this article, the evaluation of safety factor from two methodologies is compared, which allow to design the reinforcement required for the balance of vertical cuts in deep excavation.

Keywords. Excavation, volcanic soil, redeposited soil, factor of safety.

1. Introduction

In an important commercial and residential area, to the west of Mexico City a 162 m height tower is built that requires an excavation of 28 m for parking basements in a zone where sand has been mined for decades, later this abandoned mine was found covered with materials from other excavations. In this case during the construction, variations were detected in relation to stratigraphic design model, so a complementary exploration campaign was made to adapt geotechnical design to real conditions, both foundation solution and stability of vertical cuts underwent changes [1]. Thus, based on the multiple stability analyzes for vertical cuts, the importance of safety factor concept and uncertainties associated with minimum admissible values were speculated.

2. Geotechnical conditions

The property upon which this Project is located is in the geotechnical zone of Lomas, in an area where sand has been mined since the 1930s, an activity that saw a boom in later decades. This activity brought about a hollow, or depression, measuring 4 km long by 2 km wide, which in some areas reaches up to 100 m deep. Starting in 1960, with increasingly deep excavation, the costs of exploitation increased, and the mines began to be sold. Lands acquired by the government were used as landfills for years. In the 1990s, the last sanitary landfill was closed, and the Santa Fe development began. Therefore, in this area properties exist whose subsoil is characterized by having heterogeneous garbage fillers, byproducts of excavations, demolition waste, and natural erosion to the topography.

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2.1. Topography

The property has a topography with important slopes, that measure 20 m both in the NW-SE (Vasco de Quiroga avenue -Mexico Toluca Highway) direction, as well as in the SW-NE direction (direction of Vasco de Quiroga avenue), however, in the first case, the slope drops to SE 23.5%, while towards the NE the slope is 5.5% (Figure 1).

2.2. Stratigraphic interpretation

The site under study consists of several plots of land, explored by standard penetration test, open-pit mines, and in situ trials with a phicometer (Figure 1). With the interpretation of old aerial photographs and the geological study, it was established that on the boundary with Vasco de Quiroga avenue there was a depression in the natural terrain, associated with a mine that was exploited in the 1970s. According to geotechnical exploration three deposits were detected (Figure 2): 1) Filling, from 0 to 25 m depth,(CH) reddish brown high plasticity clay, of soft to medium consistency, with sand and gravel, 2) Pyroclastic flow (Arena azul), from 25 to 40 m depth, (SM) fine medium and thick fine sand, andesitic, quartzose and angular, with gray silt, gravels and pyroclastic rounded rocks, 3) Pyroclastic flow (Cuquita), from 40 m, (SM) fine, medium and thick sand, pumice, quartz and angular, with light brown and brownish-pink mud, with gravels and cobblestones. On the other hand, no phreatic level was detected in the site.

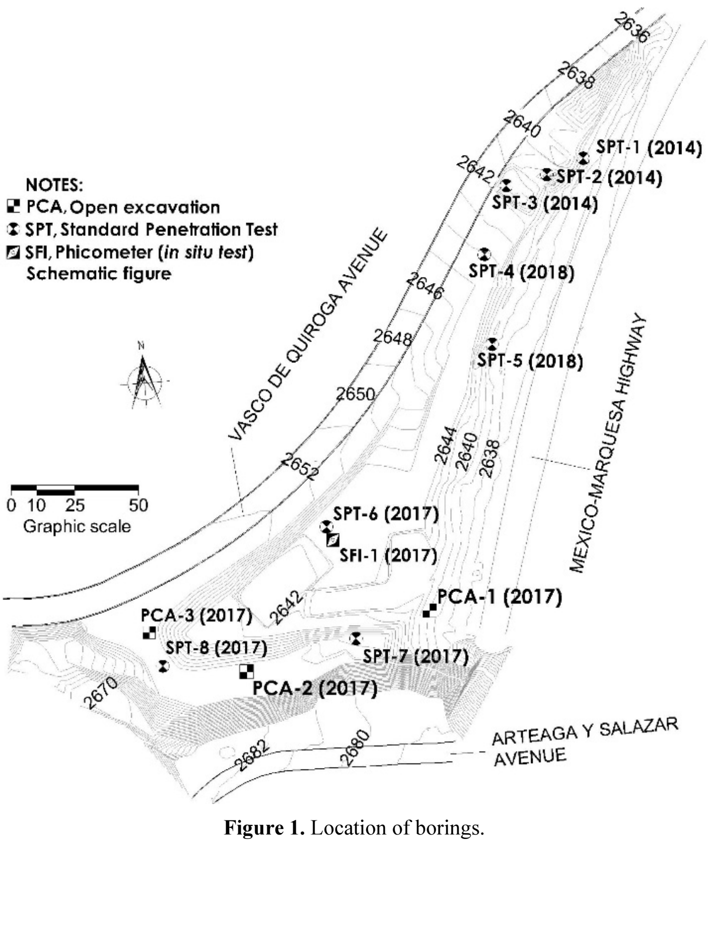


Figure 1. Location of borings.

2.3. Geotechnical model design

Table 1 shows the mechanical properties considered in the geotechnical design, due to the fact that unaltered sampling was not feasible, in detected deposits in situ tests were made with a phicometer. It should be noted that using of this tool is increasingly widespread in Mexico, due to the reliability of the results obtained [6, 3], based on the tests carried out by highly trained technicians with expertise.

Table 1. Geomechanical design.

Layer	Depth (m)	γ (kN/m^3)	c (kPa)	ϕ (°)	E (MPa)
Fill	0-12.0	17	30	20	10
Pyroclastic flow	>12.0	18	60	39	300

γ, unit weight; c, cohesion; ϕ, angle of internal friction; E, Young's modulus.

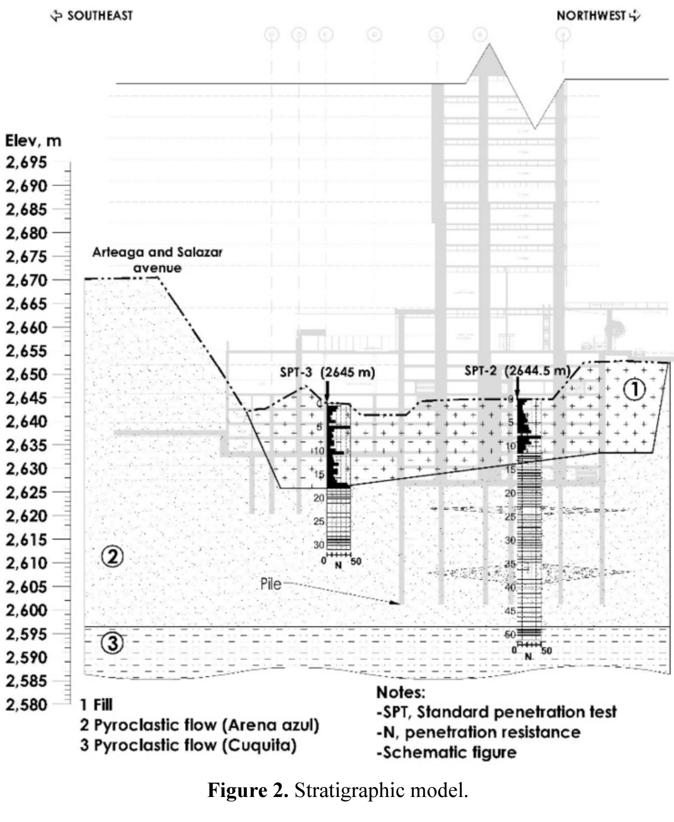


Figure 2. Stratigraphic model.

3. Geotechnical design

3.1. Stabilization system

Due to land's topography cut-slope height was variable 6 m to 28 m. Lateral support system for slopes higher than 10 m, consisted of a shotcrete with post-tensioned anchors which loads varied from 1,000 to 2,200 kN; grouted with slurry that is 15 MPa of strength at 1 MPa of pressure. In this excavation 1,022 anchors were installed, Figure 3 shows an anchor section at Vasco de Quiroga avenue boundary.

It should be noted that compound slopes were formed in south boundary, whose upper slope was constituted by the natural land, while lower slope corresponds to the excavation of basements; in these cases, total slope was 50 meters high.

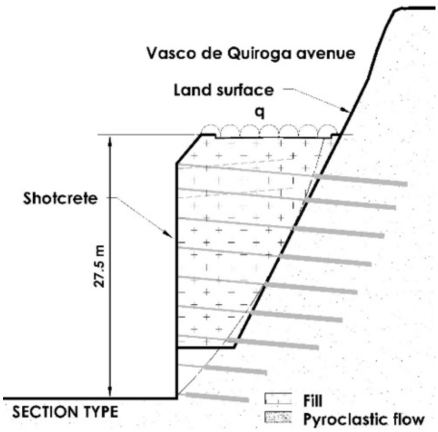


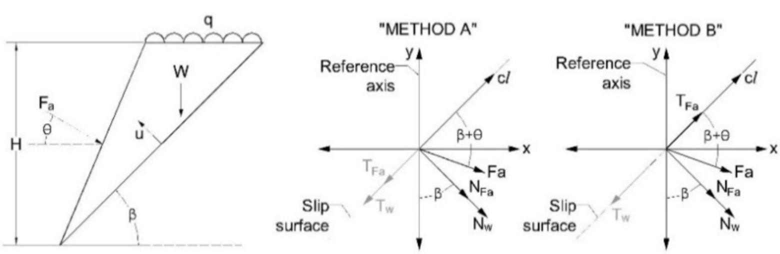
Figure 3. Support type section.

3.2. Factor of Safety calculation

In stability of slopes Factor of Safety evaluate the risk of failure, numerically this index is determined as a ratio of the strength forces (shear strength) and the perturbing forces (shear strength at failure). Considering this definition and the Hoek [4] criterion, based on a limit equilibrium model for plane failure, as representative method of soil behavior found, some stability analysis of slopes was made for this project.

Figure 4 shows analytical model, including reinforcement force required to maintain the equilibrium condition, when FS=1. It should be noted that the FS value is an index to evaluate the failure risk, internationally, values between 1.1 and 1.3 are accepted [2] accounting uncertainties of the analysis conditions and consequences of eventual failure I this case, admissible values between 1.5 to 2.0 are accepted [5], for determining reinforcement to the slope, it was taken into account the increase of the resistant force by anchoring force.

From analysis model in Figure 4, Factor of Safety is calculated by two methods:



Notes: N_w=Wcosβ; T_w=Wsenβ; N_{Fa}=Fasen(β+θ); T_{Fa}=Facos(β+θ); Factor of Safety calculation for a slope with no tension crack; the water pression is zero.

Figure 4. Vector Analysis.

Method A, considers the component of the anchoring force, so that resistant force increases and motor force decreases, in this case FS grows exponentially (Eq. 1). This criterion is associated with tension anchors [5].

Method B, Strength resistant increases as function of the anchorage, in this case, FS grows proportionally with reinforcement (Eq. (2)). This criterion corresponds with reinforcement elements designed to work until the slope slides [5].

$$FS = \frac{cl+[W\cdot cos\,\beta+F_A\cdot sin(\beta+\theta)-F_{sis}\cdot sin\,\beta]\,tan\,\varphi}{W\cdot sin\,\beta+F_{sis}\cdot cos\,\beta-F_A\cdot cos(\beta+\theta)} \tag{1}$$

$$FS = \frac{cl+[W\cdot cos\,\beta+F_A-F_{sis}\cdot sin\,\beta]\,tan\,\varphi}{W\cdot sin\,\beta+F_{sis}\cdot cos\,\beta} \tag{2}$$

where *c*, cohesion; *l*, length of sliding surface; *W*, weight of soil; *Fa*, force of support; *β*, angle of failure surface; *θ*; inclination of anchor.

3.3. Stability Analysis

Due to stratigraphic characteristics of the site and architectural project changes, several slopes were analyzed; this paper presents three examples to establish differences between calculation Methods A and B; *Case 1*, vertical slope in pyroclastic flow 47.5 meters high with an intermediate berm at 20 m measured from the crest; *Case 2*, vertical slope in redeposited soil 13 meters high; *Case 3*, stratigraphic vertical slope 27.5 meters high: 13 meters of redeposited soil and 14.5 m of pyroclastic flow. Note graphs present calculations for Factor of Safety from 1 to 6 *versus* anchor force, to show results dispersion; also differences between two calculation Methods for SF=1.3, 1.5, 1.7 and 2; it includes anchorage design for the reference project.

3.4. Results

Figure 5 shows the results of *Case 1*, for the slope that is 47.5 meters high, it was observed that the methods converge for a SF=1.2, associated with an anchor force of 400 kN; when SF=2, Method B requires 41% more anchor force than which was determined by Method A.

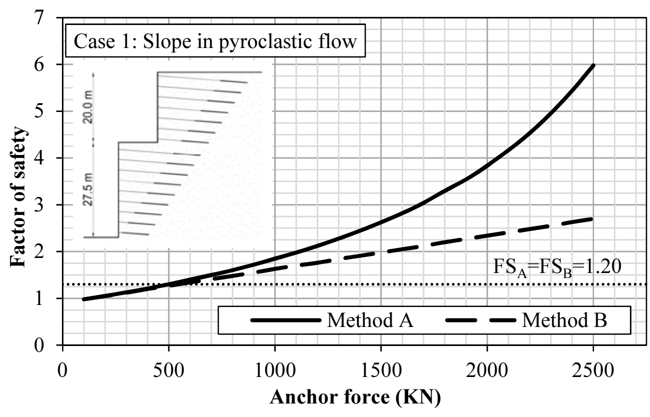


Figure 5. Results of Case 1: Slope in pyroclastic flow.

The results of *Case 2* are presented in Figure 6, this slope is three-and-a-half times less than the previous one; that is to say, with a SF=1.1 both methods converge; likewise, the difference in the results increases, since Method B requires 64% more anchor force than Method A, to arrive at an SF=2.

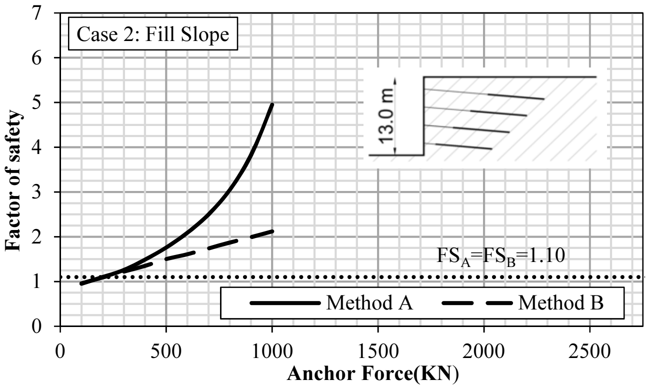


Figure 6. Results of Case 2: Fill Slope.

In the case of a stratigraphic slope, the results are shown in Figure 7; for this 27.5 m slope, the rate of convergence was SF=1.14; to achieve SF=2, Method B required 40 % more anchor force compared to Method A.

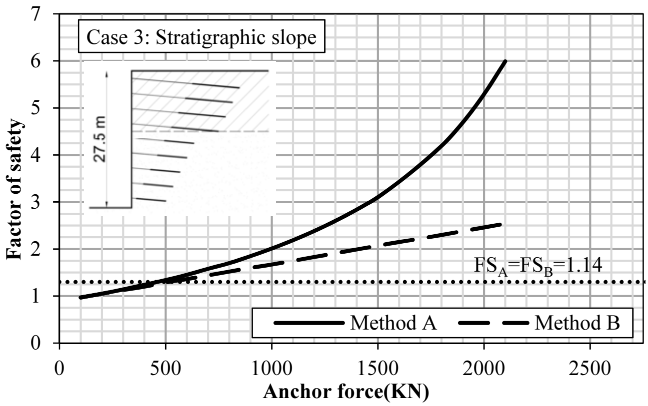


Figure 7. Results of Case 3: Stratigraphic slope.

A summary of the results is shown in Table 2, for the three analyzed cases, outlining the calculations for the usual Factor of Safety (FoS) of 1.3, 1.5, 1.7 and 2; in order to evaluate the differences between Methods A and B, the value for the increase in anchor force is included. It can be observed that dispersion increases with higher Safety Factors. In this way, for the SF=1.5 the anchor force can be increased up to 25%; from this value the dispersion is greater. In this revision, it reached 64% for the 13 m high slope, for a SF=2.

Finally, Figure 8 presents design results for different slopes, for which SF=1.7 was requested, because property for this project borders on important roads and federal infrastructure work; likewise, due to heterogeneity of redeposited soil and uncertainty of time to excavate. This summary shows that slopes less than 15 meters high present the greatest dispersion between Methods A and B; and higher slopes have differences around 20%.

Table 2. Summary of results for the three cases analyzed.

FOS	Anchor Force (KN)								
	Slope in pyroclastic flow			Fill slope			Stratigraphic slope		
	A	B	Δ (%)	A	B	Δ (%)	A	B	Δ (%)
1.3	500	550	10	350	350	0	450	550	22
1.5	700	850	21	400	500	25	650	800	23
1.7	850	1100	29	450	650	44	800	1050	31
2.0	1100	1550	41	550	900	64	1000	1400	40

FOS, factor of safety; A y B, Methods of analysis; Δ, increase in the anchor force compared to the result with method A

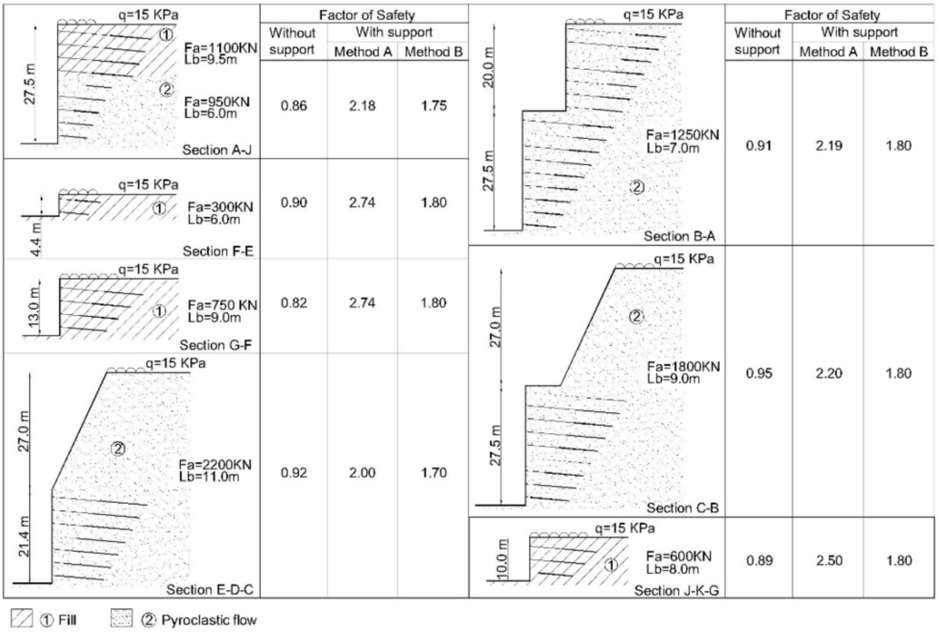


Figure 8. Design results of slopes.

4. Discussion

In this project the stability analysis was made from a limit equilibrium model for plane failure, in order to determine the anchoring force needed to reach a FS=1.7. The main disadvantage of this methodology of analysis used in ordinary engineering practice, is that stress-strain characteristics of the material are not taken into account, in addition, the considerations of analysis and Factor of Safety are homogeneous along the potential surface of failure, among others. However, the approximation of this method is sufficiently useful for the reference project.

Factor of Safety is associated to the uncertainty of analysis conditions, including evaluation of the strength, constructive practices and collateral damages associated with a possible failure. Establishing values of admissible FoS will depend on the previous experience and judgment of engineer, as well as the codes or manuals that govern the design.

In this case, solution was based on method B, because it respects definition of FoS, only the increase in resistant forces due to the effect of the anchors is accepted which has proved reliable in our company´s experience.

The method A that considers decomposition of forces, eventually leads to more economical designs, in comparison with method B. However, if analysis uncertainties are reduced and FS≤1.3 are accepted, the differences between these methodologies are negligible.

The purpose of this comparison is to highlight that analysis of slope stability and design of reinforcement elements, will depend on the experience acquired by the designer and good judgment to establish the analysis conditions. Using one of the methods presented or requesting a higher safety factor would not be the guarantee of stability.

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