Experimental and numerical study on the behavior of soil nailing excavations in volcanic soils

Étude expérimentale et numérique sur le comportement des excavations par clouage de sol dans les sols volcaniques

Vicente E. Capa & Pedro A. Calderón
Department of Construction Engineering and Civil Engineering Projects, Universitat Politècnica de València, Valencia, Spain, vicagua@doctor.upv.es

F. Javier Torrijo
Department of Geotechnical and Geological Engineering, Universitat Politècnica de València, Valencia, Spain Research Centre PEGASO, Universitat Politècnica de València, Valencia, Spain

ABSTRACT: An experimental and numerical analysis is presented in this study carried out on the behavior of a Soil Nailing System in volcanic soils, for the construction of a 5-level underground vehicle parking structure of an important building located in the north-central sector of the city of Quito (Ecuador). The numerical analysis was performed using constitutive models: Mohr-Coulomb, Hardening Soil, and Hardening Soil with Small Strain Stiffness, while the experimental study was carried out through instrumentation and monitoring activities on the soil nails, wall, and ground using Strain Gauges and measurement marks or points conveniently installed in each of the structure's components. The monitoring process took place simultaneously during each stage of the construction. Thus, numerical and experimental data were obtained for each construction phase, providing a range of variation and approximation for axial stress forces on the soil nails, horizontal displacements of the wall, and ground settlement behind the wall.

RÉSUMÉ : Une analyse expérimentale et numérique est présentée dans cette étude réalisée sur le comportement d'un système de clouage de sol dans les sols volcaniques, pour la construction d'une structure souterraine de stationnement de véhicules à 5 niveaux d'un bâtiment important situé dans le secteur nord-central de la ville de Quito (Équateur). L'analyse numérique a été réalisée à l'aide de modèles constitutifs: Mohr Coulomb, Hardening Soil and Hardening Soil with Small Strain Stiffness, tandis que l'étude expérimentale a été réalisée par des activités d'instrumentation et de surveillance sur les clous du sol, mur, et mise à la terre à l'aide de jauges de contrainte et de repères ou points de mesure installés dans chacun des composants de la structure. Le processus de surveillance s'est déroulé simultanément à chaque étape de la construction. Ainsi, des données numériques et expérimentales ont été obtenues pour chaque phase de construction, fournissant une gamme de variations et une approximation des efforts axiaux sur les clous du sol, des déplacements horizontaux de la paroi et du tassement du sol derrière la paroi.

KEYWORDS: Soil nailing; geotechnical characterization; constitutive soil model; volcanic soils; monitoring.

1 INTRODUCTION

The soil nailing technique is a ground reinforcement procedure consistently used to stabilize slopes and land sections in geotechnical engineering projects. This technique is frequently used in the city of Quito (Ecuador) to reinforce the ground and improve slope stability during the excavation process for various underground parking levels. Such deep excavations are common in the city's most important real estate projects, in which soil nailing is used with different variations that are adjusted per the construction resources available in the particular environment. However, this technique, which has proven to be effective for soil excavations in the city of Quito, currently has limited local research based on the geotechnical properties of the area's typical volcanic soils characteristic, whether theoretical, numerical, or experimental. (Capa 2021).

The soil nailing technique has been used worldwide in several engineering projects in countries such as The United States (Turner & Jensen 2005), Chile (Villalobos et al. 2013), China (Zhu et al. 2013), Ireland (Menkiti et al. 2013), and Brazil (Ehrlich & Silva 2015), among others. Similarly, several numerical studies have been carried out on the behavior of this type of structures, such as those presented by Fan & Luo (2008), Singh & Sivakumar Babu (2009), Wei & Cheng (2010), Rabie (2016), and Rawat & Gupta (2016), among others.

Conversely, several researchers have presented certain experimental studies on the behavior of soil nailing structures. Among these studies, the Clouterre French research project, which began in 1986, included large-scale testing and monitoring of nailed walls and numerical simulations (Clouterre 1991). Likewise, the experimental project called the "Amherst Test Wall" began in 1996 at the University of Massachusetts Amherst (USA), and consisted of a large-scale wall that was equipped with instruments to investigate its failure mode (Sheahan 2000). Meanwhile, Holman & Tuozzolo (2009) presented a study of a temporary "Soil Nail Wall" constructed in Manhattan (United States) and the main objective was to investigate the distribution of tensile forces on the anchor bars. Garzón et al. (2019) presented a comparative study of the suitability of using limit equilibrium and finite element methods for the design of nailed structures based on the "Amherst Test Wall" project.

This study shows the behavior of an excavation performed with the soil nailing technique for the construction of a 5-level underground parking area (h=13.55 m) of an important building constructed in the north-central area of the city of Quito between 2016 and 2018. The research contemplates an experimental approach (instrumentation and monitoring) and a numerical analysis using finite elements with Plaxis 2D (Plaxis 2020), with the application of Mohr-Coulomb (MC), Hardening Soil (HS), and Hardening Soil with Small-Strain Stiffness (HSsmall) constitutive soil models. Both the experimental and numerical studies will focus on the evolution of the tensile forces in the anchor bars, the analysis of horizontal displacements of the facing, and the ground settlements inferred by the construction of each basement level.

Furthermore, the process of obtaining geotechnical parameters for each of the soil constitutive models to be used in the numerical analysis is supported by a complete geotechnical characterization campaign with field borings and specialized laboratory tests, intentionally performed as part of this study. The various activities for this research were carried out with the support of the Soil Mechanics Laboratory of the Geotechnical Engineering Department and the Structures Laboratory of the Institute of Concrete Science and Technology (ICITECH) of the Universitat Politècnica de València.

2 GEOTECHNICAL CHARACTERIZATION

2.1 *Location of the Study Area*

Figure 1 shows the location of the soil nailing structure subject-matter of this study, located on Avenida Río Amazonas, in the north-central area of the city of Quito.

Figure 1. Location of the soil nailing structure in the city of Quito.

2.2 *Methodology*

As a previous phase of this study, a complete geotechnical characterization study of the sector was carried out, based on drilling with standard penetration tests (SPT) and a complete campaign of laboratory tests to determine the main characteristics of the soils: index properties, compressibility, shear strength and deformation parameters under deviatoric stress. According to the requirements of the geotechnical parameters for each soil constitutive model, testing consisting mainly of conventional oedometric tests with double drainage (top and bottom), consolidated undrained triaxial tests (CU) and consolidated drained triaxial tests (CD) were performed to evaluate compressibility, and strength and stiffness, respectively. Conversely, to complement the research, X-ray diffraction (XRD) and Scanning Electron Microscopy (SEM) tests were carried out to determine the mineralogical and microstructure characteristics and to evaluate their influence on mechanical behavior.

2.3 *Geotechnical Parameters*

The geotechnical characterization study determined that the subsoil in the project area consists of volcanic soils containing mainly sands and, to a lesser extent, silts and clays of low and medium plasticity. In general, specimens of certain soil strata with low density and specific gravity values were identified. Some images from Scanning Electron Microscopy (SEM) tests indicated the presence of gas bubbles and organic matter (See Figure 2), which could be the main reason for such low-density values (Capa 2021).

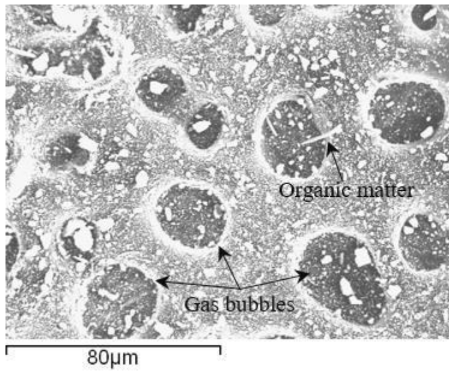

Figure 2. SEM micrograph of soil specimen from the area. The presence of gas bubbles and organic matter is observed.

Additionally, mineralogy and microstructure analyses determined mainly the presence of plagioclases and, in general, pyroclastic materials of andesitic composition. The presence of silica is also highlighted, which would be a dominant cementation agent in the material.

In this study, 2 main soil strata were identified (0-6 m and 6-14 m), for which the respective geotechnical parameters were determined. Conversely, the soil strength parameters were determined through the CU and CD triaxial tests, while the stiffness parameters were determined exclusively by the CD triaxial tests.

Table 1 shows the parameters determined for the application of the Mohr-Coulomb (MC) soil constitutive model.

Table 1. Geotechnical parameters for the Mohr Coulomb constitutive model.

Parameter	*0 - 6 m*	*6 - 14 m*
Effective cohesion, c' (kN/m^2)	15	69
Effective friction angle, ϕ' (º)	34	36
Dilatancy angle, ψ (º)	4	6
Soil unit weight, γ (kN/m^3)	18	19
Young's modulus, E' (kN/m^2)	41667	85714
Poisson's ratio, ν' (-)	0.3	0.3
Overconsolidation ratio, OCR (-)	1.4	1.5
Coefficient of earth pressure at rest of the overconsolidated soil, K_0 (-)	0.517	0.493

By the other hand, Table 2 presents the parameters obtained for the Hardening Soil (HS) constitutive model.

Table 2. Geotechnical parameters for the Hardening Soil constitutive model.

Parameter	*0 - 6 m*	*6 - 14 m*
Effective cohesion, c' (kN/m^2)	15	69
Effective friction angle, ϕ' (º)	34	36
Dilatancy angle, ψ (º)	4	6
Soil unit weight, γ (kN/m^3)	18	19
Secant stiffness in drained triaxial test, E_{50}^{ref} (kN/m^2)	9091	32370
Tangent stiffness for primary oedometer loading, E_{oed}^{ref} (kN/m^2)	6009	14757
Unloading / reloading stiffness, E_{ur}^{ref} (kN/m^2)	27273	97110
Reference stress for stiffness, p^{ref} (kN/m^2)	100	100
Power for stress-level dependency of stiffness, m (-)	0.60	0.60
Poisson's ratio for unloading / reloading, ν_{ur} (-)	0.2	0.2
Coefficient of lateral stress in normal consolidation, K_0^{NC} (-)	0.441	0.412
Overconsolidation ratio, OCR (-)	1.4	1.5
Coefficient of earth pressure at rest of the overconsolidated soil, K_0 (-)	0.517	0.493

Application of the Hardening Soil with Small-Strain Stiffness (HSsmall) soil constitutive model requires the same parameters as the Hardening Soil model, but also with the additional parameters shown in Table 3.

Table 3. Additional geotechnical parameters for HSsmall constitutive model.

Parameter	*0 - 6 m*	*6 - 14 m*
Shear modulus at very small strains, G_0^{ref} (kN/m^2)	57639	110693
Shear strain at which $G=0.7G_0$, $\gamma_{0.7}$ (-)	3.86×10^{-4}	4.51×10^{-4}

3 FACING AND SOIL NAIL PROPERTIES

Table 4 shows the axial stiffness EA and flexural rigidity EI, for the 0.25 m thick reinforced concrete facing of the soil nailing structure.

Table 4. Stiffness parameters for Soil Nailing structure facing.

Parameter	*0 - 6 m*	*6 - 14 m*
Axial stiffness, EA (kN/m)	57639	110693
Flexural rigidity, EI ($kN.m^2/m$)	3.86×10^{-4}	4.51×10^{-4}

Soil nail stiffness parameters were determined based on an equivalent modulus of elasticity, considering the 0.15 m borehole diameter, the 25 mm rebar section, the characteristics of the materials, and, of course, the horizontal spacing between anchors. Thus, Table 5 presents the properties of the soil nails used in each of this structure's five rows.

Table 5. Soil Nail Properties.

Basement Level	*Soil Nail Length (m)*	*Horizontal Spacing (m)*	*EA (kN/m)*	*EI ($kN.m^2/m$)*
1	15	1.50	309604	435
2	15	1.50	309604	435
3	12	1.50	309604	435
4	12	2.00	232203	327
5	9	2.00	232203	327

4 NUMERICAL STUDY WITH FINITE ELEMENTS

|The soil nailing structure has 5 basement levels and a total excavation of 13.55 m, which was carried out through 5 partial excavations, each representing the height of a basement level (See Figure 3). The numerical analysis was performed using the finite element method with Plaxis 2D V20. 15-node elements and a "very fine" element mesh were used. Initial stresses were generated with the K0 procedure. Standard interfaces were included in the soil nails to simulate and take into consideration the existing friction in the soil-anchor interaction. The value considered for the strength of the interfaces is R_{inter} = 0.67.

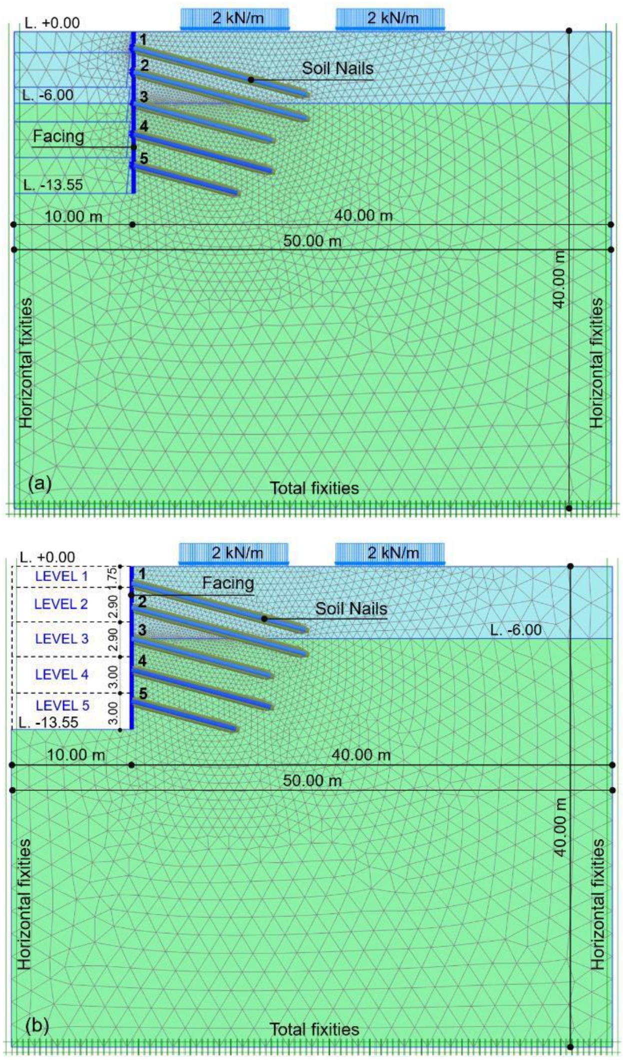

Figure 3. Numerical model with Plaxis 2D: (a) Initial model and (b) Final model with 5 basement levels built.

Figure 4 presents the soil nailing structure analysis with the construction of basement level 5, which is the phase with the greatest displacements, applying the 3 soil constitutive models: MC, HS, and HSsmall, respectively. In the analysis with the MC model, high values of soil uplift were noticed at the bottom of the excavation, as this constitutive model includes only one stiffness module for analysis of the loading and unloading process, unlike the HS and HSsmall models which include an unloading/reloading stiffness module E_{ur}, which represents the soil behavior in loading and unloading conditions. Therefore, these 2 soil models (HS and HSsmall) better represent the behavior of excavations.

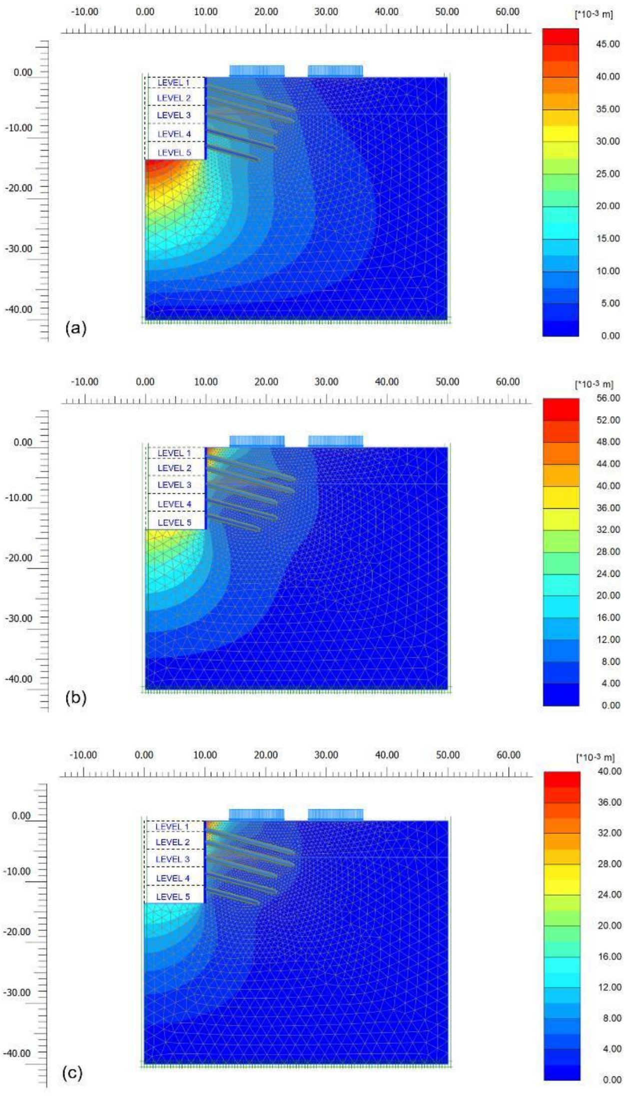

Figure 4. Total displacements |u|: (a) Mohr Coulomb, (b) Hardening Soil and (c) HSsmall.

5 EXPERIMENTAL STUDY

5.1 *Structure instrumentation and monitoring*

The experimental study included instrumentation and monitoring tasks. As part of this study, therefore, to estimate the parameters that characterize this type of anchored structures, strain gauges (HBM brand type K-LY4) were installed on the steel bars of the soil nails every certain distance, to determine the magnitude of the axial force on them. Leveling bases were built at the measurement points behind the cross-section of the anchored facing, to control vertical soil displacements. Furthermore, to measure horizontal facing displacements, small fixed and permanent metallic markers were installed on the facing, next to soil nail steel plates. Such instrumentation elements were built and installed simultaneously during the construction process of each basement level. Figure 5 shows the total strain gauges installed on the soil nail steel bars and the measurement points and markers built for monitoring the structure's behavior.

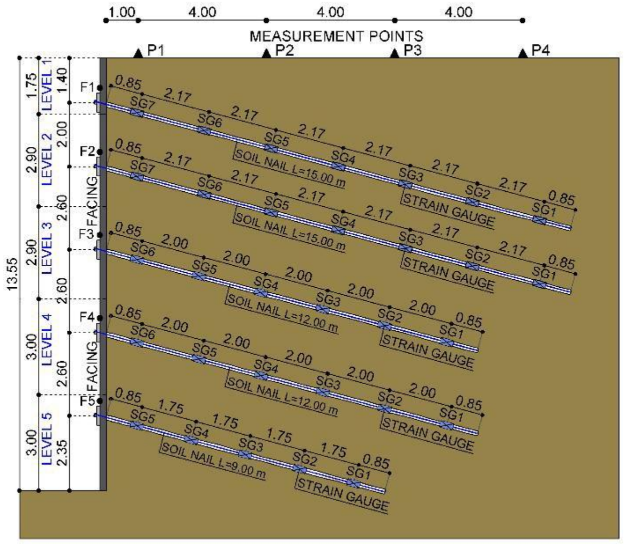

Figure 5. Instrumentation for the soil nail structure.

Figure 6(a) shows the installation of strain gauges on the soil nail steel bars. Each sensor was properly protected from external agents by using HBM AK22 bonding putty.

During the different monitoring phases of the installed strain gauges, an Omega INET-555 electronic data acquisition system, previously calibrated for this type of readings, was used. Figure 6(b) shows the periodic strain reading process obtained from the installed strain gauges.

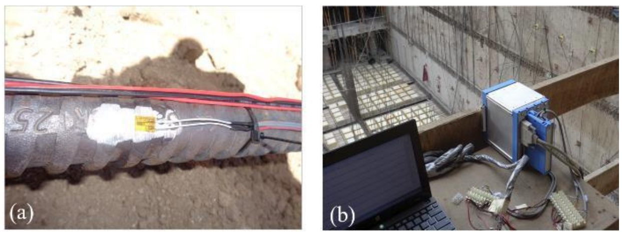

Figure 6. (a) Installation of strain gauges on soil nail bars and (b) Strain monitoring and readings from installed strain gauges.

Concurrent to the entire construction process, strain gauges were monitored, and deformation was controlled using the leveling bases and facing measurement points, with the help of surveying equipment. The construction of a new basement level involved taking readings from the new anchorage strain gauges, reviewing behavior, and storing the new strain values for the upper basement level anchorages, since there will always be variation due to the effects of the construction process itself.

5.2 *Experimental study results*

For improved interpretation, the monitoring results are presented here superimposed on the theoretical diagrams obtained from the numerical analysis using finite elements with Plaxis 2D and the three soil constitutive models. The results obtained from the construction of the final two basement levels, which are the stages where the greatest degree of stress and deformation occur, are presented. Conversely, the first construction stages are handled within the range of small strain and displacement values, which require a higher degree of accuracy and could potentially lead to a considerable estimation loss.

5.2.1 *Axial forces on soil nail steel bars*

Figure 7 shows the results of axial tension forces induced by the construction of basement levels 4 and 5, obtained from the experimental study and superimposed on the numerical study diagrams.

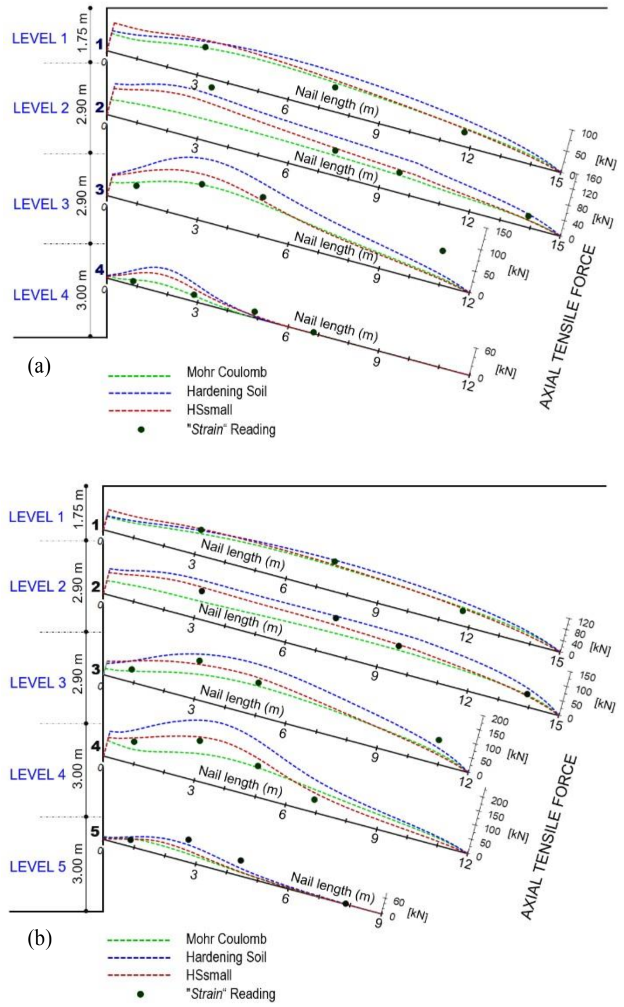

Figure 7. Axial tension forces induced by the construction of: (a) Basement 4 and (b) Basement 5.

For the construction of basement 5 (final phase, h=13.55 m), the HSsmall constitutive model values present the best approximation to the experimental values, and consequently, they show the lowest percentage error. For the case at hand, the application error of the HSsmall constitutive model ranges between 8% and 50%.

5.2.2 *Vertical and horizontal displacements*

Figure 8 shows the measurements for horizontal displacements of the facing and vertical displacements of the soil, induced by the construction of basement level 4, obtained from the experimental study and superimposed on the numerical study diagrams. Conversely, Figure 9 provides the displacements induced by the construction of basement 5.

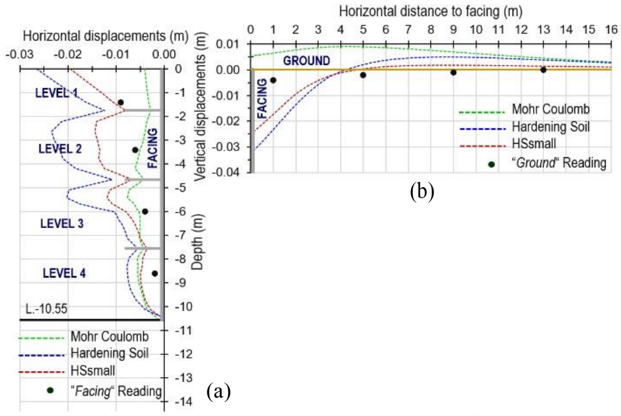

Figure 8. Displacements induced by the construction of basement 4: (a) Horizontal facing displacements and (b) Vertical ground displacements.

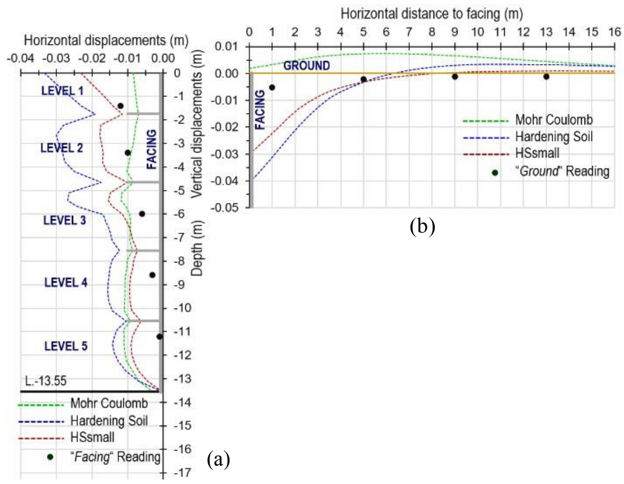

Figure 9. Displacements induced by the construction of basement 5: (a) Horizontal facing displacements and (b) Vertical ground displacements.

During the construction of basement level 5, horizontal displacements as determined with the HSsmall constitutive model show the best approximation to the experimental results, and therefore, they present the lowest percentage error, in this case, close to 46%.

Likewise, the vertical displacements or ground settlements obtained with the HSsmall soil constitutive model show the best adjustment or approximation to the experimental values. However, despite this, there are error percentages above 300% in the initial phases, and close to 154% in the construction of basement 5, which determines that the numerical analysis values tend to be much higher than the actual experimental study values.

6 CONCLUSIONS

As a result of the experimental and numerical study of the behavior of a soil nailing structure built in the volcanic soils of the city of Quito, the following conclusions can be drawn:

- In general and simplified terms, the tensile force measurements for the soil nails, the horizontal facing displacements, and the ground settlements recorded in the experimental study are lower than those determined in the numerical study with finite elements and the Mohr-Coulomb (MC), Hardening Soil (HS) and Hardening Soil with Small-Strain Stiffness (HSsmall) soil constitutive models.
- A comparative analysis of the results of the experimental study with the results of the numerical analysis with each soil constitutive model shows that the HSsmall model correlates

best with the experimental data for tensile forces, horizontal displacements, and settlements since these reflect the lowest error percentage compared to the Mohr-Coulomb and Hardening Soil constitutive model values. The best fit is most noticeable during the construction phase of the final basement level, which is when the highest strain and deformation measurements are induced in the soil. Conversely, during the initial construction stages, the range of smaller strain and displacement values, which require a higher degree of precision, have the potential of leading to a significant estimation loss.

- The vertical ground displacements obtained from the numerical analysis with the Mohr-Coulomb model, in most cases result in states of uplift as opposed to settlements, as in most cases with the HSsmall and Hardening Soil numerical models and the experimental survey readings. Therefore, the Mohr-Coulomb constitutive model is not the most suitable for estimating the ground settlements inferred from the excavations for the construction of the different basement levels.
- Certain soil strata studied in the area show low-density values and high void ratio and porosity values (typical characteristics of many types of volcanic soils), which, according to the microstructure analysis, is directly linked to the presence of gas bubbles in the soil structure. It follows, therefore, that this type of soil requires a thorough analysis from the unsaturated soil viewpoint since the suction effect can directly contribute to an increase in soil stiffness and more specifically, to an increased cohesion value. Therefore, a significant increase of cohesion in the analysis of a geotechnical engineering structure can significantly change the results of the numerical analysis.

7 ACKNOWLEDGEMENTS

This research was supported and financed by CIMENTEST Ingeniería y Proyectos Cia. Ltda. (Ecuador) with technical support from the Departments of Geotechnical Engineering and Construction Engineering of the Universitat Politècnica de València. Their valuable contribution is much appreciated.

8 REFERENCES

Capa, V.E. 2021. Estudio experimental y numérico del comportamiento de excavaciones ejecutadas mediante la técnica de suelo claveteado (soil nailing) en suelos de la ciudad de Quito (Ecuador) [Tesis doctoral]. Universitat Politècnica de València. https://doi.org/10.4995/Thesis/10251/164174.

Clouterre 1991. Recommendations CLOUTERRE 1991 - Soil Nailing Recommendations 1991, English Translation, *Presses de l'Ecole Nationale des Ponts et Chaussées*, Paris, France.

Ehrlich, M., and Silva, R.C. 2015. Behavior of a 31 m high excavation supported by anchoring and nailing in residual soil of gneiss. *Engineering Geology* 191 (2015), 48-60.

Fan, C.C., and Luo, J.H. 2008. Numerical study on the optimum layout of soil-nailed slopes. *Computers and Geotechnics* 35 (2008) 585-599.

Garzón, J., Capa, V.E., Torrijo, F.J., and Company, J. 2019. Designing Soil-Nailed Walls Using the Amherst Wall Considering Problematic Issues during Execution and Service Life. *International Journal of Geomechanics* 19(7): 05019006.

Holman, T.P., and Tuozzolo, T.J. 2009. Load Development in Soil Nails from a Strain-Gauge Instrumented Wall. Contemporary Topics in Ground Modification, Problem Soils, and Geo-Support, *2009 International Foundation Congress and Equipment Expo*, Orlando, USA, 25-32.

Menkiti, C.O., Long, M., Milligan, G.W.E., and Higgins, P. 2013. Soil Nailing in Dublin Boulder Clay. *Geotech Geol Eng* (2014) 32:1427-1438.

Plaxis 2020. Plaxis 2D Reference Manual. Connect Edition V20. Delf, The Netherlands.

Rabie, M. 2016. Performance of hybrid MSE/Soil Nail walls using numerical analysis and limit equilibrium approaches. *HBRC Journal* (2016) 12, 63-70.

Rawat, S., and Gupta, A.K. 2016. Analysis of a Nailed Soil Slope Using Limit Equilibrium and Finite Element Methods. *Int. J. of Geosynth. and Ground Eng.* (2016) 2:34.

Sheahan, T. 2000. A field study of soil nails in clay at the UMass NGES. *National Geotechnical Experimentation Sites, Geotechnical Special Publication 93*, edited by J. Benoit and A. J. Lutenegger, 250-263. Reston, VA: ASCE.

Singh, V.P., and Sivakumar Babu, G.L. 2009. 2D Numerical Simulations of Soil Nail Walls. *Geotech Geol Eng* (2010) 28:299-309.

Turner, J.P., and Jensen, W.G. 2005. Landslide Stabilization Using Soil Nail and Mechanically Stabilized Earth Walls: Case Study. *Journal of Geotechnical and Geoenvironmental Engineering* 131(2): 141-150.

Villalobos, S.A., Oróstegui, P.L., and Villalobos, F.A. 2013. Re-assessing a soil nailing design in heavily weathered granite after a strong earthquake. *Bull Eng Geol Envirom* (2013) 72: 203-212.

Wei, W.B., and Cheng, Y.M. 2010. Soil nailed slope by strength reduction and limit equilibrium methods. *Computers and Geotechnics* 37 (2010) 602-618.

Zhu, F., Miao, L., Gu, H., and Cheng, Y. 2013. A case study on behaviors of composite soil nailed wall with bored piles in a deep excavation. *J. Cent. South Univ.* (2013) 20: 2017-2024.