Analysis of the deformational behavior of a clayey foundation soil stabilized with ladle furnace slag (LFS) using a finite element software

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Abstract

The stabilization of soft clayey soils to improve their stress-strain behavior is one of the most widely used geotechnical engineering techniques. Traditionally, lime and cement have been used as stabilizers, although other products such as Ladle Furnace Slag (LFS) are now used, given the environmental imperative to reuse materials and to reduce both the consumption of raw materials and the use of landfill sites. LFS is a by-product of the steelmaking industry, with limited applicability in other industrial processes, but its chemical composition, rich in calcium, magnesium, silica, and alumina, mean that it may be used as a binder for clayey soils as a substitute for lime. This geo-mechanical research is focused on the analysis of the plastic behavior and the strength of a low bearing capacity clayey soil mix with 5% added LFS. The following properties were evaluated: plasticity (Atterberg limits), California Bearing Ratio (CBR), Unconfined Compression Strength (UCS), and direct shear strength. The evolution of UCS was verified through tests on samples held in a humid chamber at a constant relative humidity of 95% ± 5%. and temperature of 20ºC± 3ºC, after 3, 7, 28, 54, and 90 days of curing. Based on the results, a numerical analysis was performed with a two-dimensional finite element software: RS2 (Rocscience). The behavior of a footing-foundation system supported on stabilized soil was modeled, with a plate load test geometry and with the laboratory parameters. The results, compared with those obtained with untreated soil and with a lime-stabilized soil, demonstrated that the LFS mix increased the stiffness of the layered soil (less settlement) and improved its bearing capacity. The applicability of LFS for soil stabilization and its use in geotechnical works such as foundations and embankments open up fields of application that are likely to offer satisfactory alternatives for these by-products.

Keywords: bearing capacity, ladle furnace slag, finite element analysis, settlement, soil stabilization.

1. Introduction

In the construction of linear works and any other engineering activities requiring large-scale earthworks, it is essential to minimize and to compensate the earthworks as much as possible, due to economic, environmental, and technical considerations. The use of all materials directly available on site, regardless of their properties, including materials with low bearing capacity, is becoming increasingly necessary.

Soils with significant clay and silt contents present serious geotechnical problems for their use in infrastructural construction, due to their high plasticity, low bearing capacity and volumetric instability that is dependent on humidity. The treatment and stabilization of these soils with lime or cement is a very satisfactory solution, being one of the oldest and most widespread soil improvement techniques. However, several investigations are being conducted on the use of other types of materials, mainly waste materials [1] with the purpose of prolonging their lifecycles, and in order to reduce the economic and environmental impact of the use of natural stabilizers

The global steel industry, a sector in continuous expansion, produced 1,950.5 million tons (Mt) of crude steel in 2021 [2]. A large volume of steel waste is generated during the steelmaking process, mainly slag, composed of metallic oxides, whose composition depends on the steelmaking furnaces and processes. Annual world production of slag is estimated to be between 10-15% of crude steel production [3]. Fortunately, many of these by-products find reutilization in building and civil works, reducing the consumption of natural resources and avoiding waste disposal.

Ladle Furnace Slag (LFS) is a by-product generated in secondary or basic steel refining. Approximately 30 million tons per year are globally generated [4], and because of its limited applicability, a significant amount is dumped at landfill sites. However, it has hydraulic properties due to its chemical composition, which confers it with cementitious properties. Currently, the preparation of Portland cement clinker is one of the main applications of LFS [5]. Many other applications are under investigation in the construction sector, with the possibility of totally or partially replacing cement and lime in many different productions, such as mortars, concrete, asphalts, and the soil stabilization, which is the subject of this study.

The main purpose of this paper is to analyze the advantages of using LFS industrial waste for the stabilization of low bearing capacity soil and to improve its strength properties. Subsequently, and based on the results of laboratory tests, the behavior of a footing-foundation system supported on stabilized soil was simulated. The objective was to conduct a comparison, based on the results provided by a Finite Element Method (FEM) software program, between soil stabilized with LFS and untreated soil and soil stabilized with lime. It was demonstrated that the LFS mix increased the stiffness of the foundation soil (less settlement) and improved its bearing capacity.

2. Materials and methods

2.1. Materials

A clayey soil of low bearing capacity was selected, which was not compliant with Spanish specifications for use as filling material in embankments or as base material for roads [6]. It was therefore necessary to stabilize this soil, before it could be used in engineering works. Spanish recommendations for the preparation of lime-stabilized soils [7] were used, as the LFS (fraction smaller than 1 mm) presented pozzolanic properties similar to lime and because there are no specific recommendations on the use of slag as a stabilizer. According to their final characteristics, two types of *in situ* lime-stabilized soils were established: S-EST1 ($Ev_2 \geqslant 60$ MPa, Ev_2 was the modulus of vertical deformation obtained in the second loading cycle according to load test of plate soil UNE 103808) and S-EST2 ($Ev_2 \geqslant 120$ MPa). The limits established for soils depending on the type of stabilized soil to be obtained are shown in Table 1. Having verified that the soil was susceptible to be stabilization with lime, the substitution of lime by slag as a stabilizing agent was considered, and the behavior of the mixture was tested.

Table 1. Geotechnical properties of the soil and Spanish standard requirements

Property	Soil	Spanish standards for lime-stabilized soils	
		S-EST 1	S-EST 2
% passing # 80 mm	100.0	>100%	>100%
% passing # 0.063 mm	67.7	>15 %	>15 %
Organic matter content (%)	0.94	< 2%	< 1%
Soluble sulphates (% SO3)	0.06	<0.7	<0.7
LL (%)	46.4	-	-
PL (%)	23.3	-	-
PI (%)	23.1	>12	12<PI<40
Free Swelling Index (%)	3.0	<3	<3
Collapse Index (%)	0.3	<1	<1

Several tests were carried out to identify and to characterize the clayey soil: granulometric analysis, Atterberg limits, and quantifications of organic matter and sulfate content, the results of which are shown in Table 1. Based on those results, this soil was classified as CL (low plasticity clay) according to the Casagrande classification (USCS Classification). The LFS slag used in this study is a by-product of steel refining processes at a pipe factory in Spain. A commercial hydrated lime was chosen for the lime used in the control samples.

Table 2 shows the chemical composition by weight of the main oxides present in the materials used in this work. These percentages were determined using the X-Ray Fluorescence (XRF) technique. The presence of reactive SiO_2 and $Ca(OH)_2$ in LFS implies that it can show self-cementing properties and pozzolanic properties as a binder [8], as several researchers have confirmed [9, 10].

Table 2. Chemical composition of soil and binders (% by weight).

Weight (W %)	Soil (W %)	LFS (W %)	Lime (W %)
CaO	26.82	56.7	92.3
SiO_2	45.25	17.7	1.20

MgO	8.25	9.60	1.40
Fe_2O_3	3.51	2.20	0.30
Al_2O_3	10.85	6.60	2.10
SO_3	0.25	0.92	0.10
MnO	0.05	0.31	N.D.
TiO_2	0.38	0.34	0.80
$K_2O + Na_2O$	2.55	0.10	0.90

2.2. Mix design

The mixing of a clayey soil with a stabilizer was designed to achieve a material of greater strength and stability. For the reference mix, it was decided to work with 2% lime, as that is the minimum amount established by Spanish regulations for stabilized soils with lime. The amount of LFS considered for the LFS mix design was 5 %. A percentage that optimized resource consumption, in order to achieve similar improvements with slag and with lime, based on the findings of previous research carried out with similar materials [11, 12]. Furthermore, the performance of the non-stabilized soils was also evaluated. So, the different mixes in the study were as follows:

- Soil mixed with 5% LFS
- Soil mixed with 2% lime
- Untreated soil

2.3. Experimental test

A battery of tests was carried out to determine the most relevant geotechnical properties, so as to analyze the plastic and resistant behavior of the soil and the mixes with lime and slag. These tests were as follows:

- The Atterberg limit test to determine both the liquid and the plastic limit and the plasticity index, as *per* ISO 17892-12.
- The Modified Proctor (MP) compaction test to obtain the Optimum Moisture Content (OMC) and Maximum Dry Density (MDD). The MP test was performed as *per* ASTM D1557-12.
- The California Bearing Ratio (CBR) test was performed as *per* ASTM D1883-21.
- Unconfined Compressive Strength test, according to ISO 17892-7, to estimate the stiffness of materials
- Direct shear test that determines the strength parameters, cohesion (c'), and internal friction angle (Φ'), of a soil sample subjected to shear stress, according to ISO 17892-10.

2.4. Numerical analysis

Rocscience RS 2D finite element software was used to examine how the stabilization of a clayey material affected the stress-strain properties of the foundation soil. The behavior of a footing-foundation system supported on stabilized soil was modelled with a plate load test geometry.

The material properties considered in the finite element analysis are presented in Table 3. The results of a direct shear test, cohesion (c), and internal friction angle (Φ), on the samples after 28 days of curing time were taken as strength parameters. The modulus of elasticity (E) was defined with the Thompson's equation (Eq.1)[13] based on the Unconfined Compressive Strength (UCS) value; this formula is recommended by the National Lime Association [14].

$$E\left(\frac{kN}{m^2}\right) = 68810 + 124 \cdot UCS\left(\frac{kN}{m^2}\right) \quad (1)$$

The Poisson's ratio values considered were 0.3 for clayey soils and 0.2 for both lime and LFS, according to the recommendations of Maher *et al.* [15]. A zero value for the angle of dilatation was proposed for safety reasons.

Table 3. Properties of soil and binders considered in numerical analysis.

Material Name	Unit Weight (kN/m^3)	Poisson's Ratio	Young's Modulus (kPa)	Peak Friction Angle (degrees)	Peak Cohesion (kPa)
Soil	19	0.3	132000	29	45

Soil + 5% LFS	19	0.2	205000	32	76
Soil + 2% Lime	19	0.2	164000	22	63

Figure 1 presents the scheme of the model created for the simulation. A finite 2D 14 m wide and 5 m deep domain, was designed. The model was projected with an upper level of stabilized soil, whose width (D) varied between 1, 2, and 3 meters and the depth (H) of the treated zone could be 0.25 m, 0.5 m, or 1 m. At the same time, the width of the loading zone (B) also varied between 1 m, 1.5 m, and 2 m. The rest of the material considered was untreated clay. The average number of 6-noded triangular elements was 2885 per case studied, increasing the intensity of the mesh in the soil stabilized zone. Displacements along the vertical and horizontal directions were set to zero for the bottom of the model, and horizontal deformation was restricted at the vertical lateral boundaries.

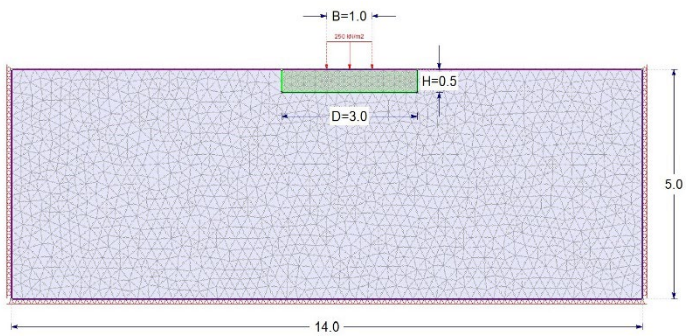

Fig. 1. Schematic representation of the finite element 2D model employed for the analysis.

3. Results and discussion

3.1. Plasticity and Mechanical Properties

- Atterberg limits

The addition of lime or slag to the clayey soil resulted in a considerable decrease in its plasticity index, which should facilitate the workability of the material (Fig. 2). In general, stabilizing a soil with lime causes an increase in the liquid and plastic limit of the mix due to the displacement of the water molecules of the diffuse double layer from the surface of the clays and their replacement by calcium Ca^{2+} ions, which leads to a slight decrease in the plasticity index [16]. However, in this clay, a slight decrease of the liquid limit was observed in the clayey mixture with lime, which generated a greater reduction of the plasticity index. For the LFS soil mix, both the liquid limit and the plastic limit increased with respect to the natural soil, however, the plasticity index showed a smaller decrease than in the case of the lime-stabilized soil. The findings reported by Montenegro *et al.* [12] in soil stabilization with similar materials confirmed a similar performance, although the slag percentages were higher.

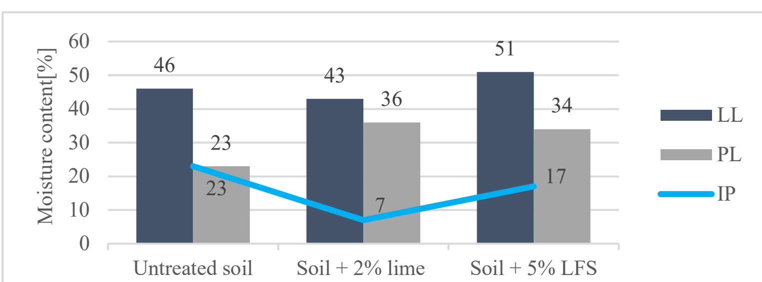

Fig. 2. Atterberg limits in soil and mixes.

- Modified Proctor (MP) compaction test

The Optimum Moisture Content (OMC) and Maximum Dry Density (MDD) were determined for the soil and the mixes sample, which were the reference values for every test performed in the present research, such as CBR and

UCS. The Modified Proctor (MP) test was performed according to ASTM D1557-12. The soil mixes varied slightly from the reference values of the untreated soil, considering the low percentages of binder added. The values obtained for the mixes with lime and LFS, which were considered equal due to the small variation between them, showed an increase in OMC and a minor decrease in MDD.

Table 4. Modified Proctor test results.

Material Name	MDD (Mg/m^3)	OMC (%)
Soil	1.75	13.50
Soil + 5% LFS	1.73	14.50
Soil + 2% Lime	1.73	14.50

- California Bearing Ratio (CBR)

The CBR index defines the bearing capacity of a soil for civil engineering works, as subgrade, subbase, and base in pavement design, or as embankment backfill. Spanish regulations [6] establish minimum CBR values requirements in each situation, in addition to other conditions. The untreated clayey soil presented a CBR value of 5.3% which meant it had the characteristics of a very low bearing capacity soil, whose destination would very probably be a landfill. After mixing the soil with 2% lime or 5% LFS, the CBR values increased to 70.4 % and 74 % respectively, which was an improvement of more than 13 times with respect to the untreated soil. Similar results have been presented by other researchers [11, 17].

- Unconfined Compressive Strength (UCS)

The UCS of both natural soil and stabilized soils was determined on 3 cylindrical specimens (3.8-cm diameter and 7.6-cm height) with Modified Proctor compaction energy, evaluated at 0, 7, 28, and 90 days of curing time, preserved in a humidity chamber at a temperature of 20ºC± 3ºC and at a relative humidity of 95% ± 5%.

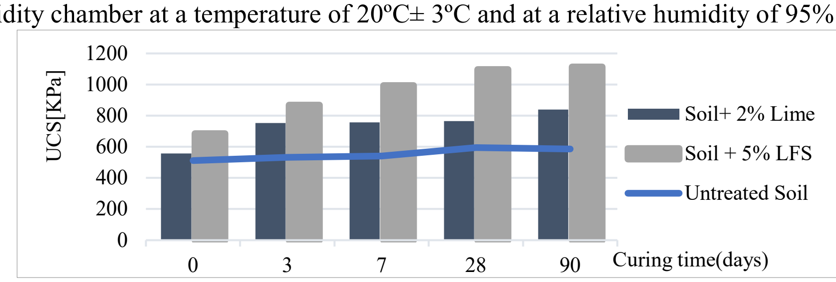

Fig.3. Unconfined compressive strength for soil and mixes over curing time.

The results are presented in Fig. 3, where it can be verified that the slag-soil mixes performed significantly better than the untreated soil in every determination, doubling the value of the UCS of the untreated soil at 90 days curing time. The lime performance was also adequate, although the values were lower than those obtained with slag; even so, it reached 1.5 times that of the natural soil at 90 days.

- Direct shear strength

This Direct Shear Strength test is essential to determine the shear strength values that were required for the numerical analysis. The evolution of these parameters was determined after 7 and 28 days of curing time of the mixes.

Fig. 4 shows that the natural soil presented a high cohesion value (45 kPa) and a medium internal friction angle (29°). After 7 days of curing, the cohesion slightly increased both in the lime mix (49 kPa) and in the slag mix (51 kPa). However, the internal friction angle decreased in the lime mix (27°) and increased considerably in the LFS mix (41°). When the curing time was extended to 28 days, the cohesion of both mixes continued to increase (63 KPa for lime and 76 kPa for LFS mix), but the internal friction angle decreased with respect to day 7 of curing (22° for the mix with lime and 32° for the mix with LFS), although in the LFS mix it improved slightly compared to the value of the untreated soil. The results for stabilized soils after 28 days of curing were used for the finite element simulation.

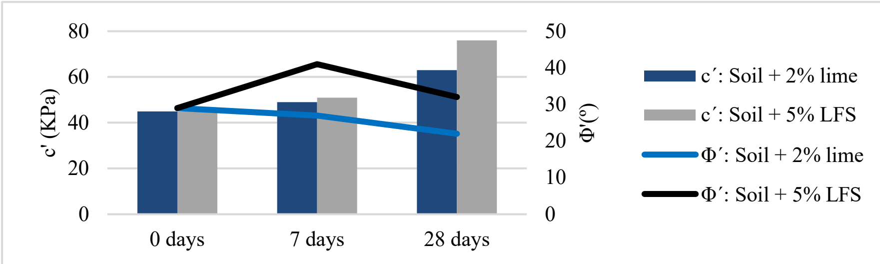

Fig.4. Evolution of c’ and Φ’ over curing time in soil and mixes.

3.2. Simulation results

Different simulations were performed, in order to investigate how the dimensions of a stabilized zone influenced the deformational behavior of the layered soil, with a RS2D finite element software. The foundation, modelled as a load plate of varied diameters [18], was subjected to increasing distributed loads. The plots of the calculated footing center settlement for the different applied loads were generated from the Rocscience RS2 Interpret software.

A total of 45 different numerical simulations were conducted where the behavior of untreated soil was compared with soils treated with lime or LFS, for different stabilized zone dimensions and varying the diameter and magnitude of the applied load. Finally, more than 500 numerical computational models were conducted.

Initially, the evolution of settlements was analyzed with the increase of the foundation loads in the cases of natural soil, soil mixed with lime, and LFS stabilized soil. The results for a stabilized zone 3 m in width and 0.5 m in depth are shown in Table 5. Lower settlement values can be observed for the soil stabilized with LFS, indicating higher stiffness of this soil. The behavior of natural soil and soil stabilized with lime showed very similar results.

Table 5. Settlements (mm) at the center of footing under different loads

Load intensity (KPa)	0	50	100	150	200	250	300	350	400	450	500
Soil	0.00	0.78	1.56	2.34	3.12	3.90	4.68	5.55	6.64	7.90	9.28
Soil +2% Lime	0.00	0.93	1.70	2.48	3.26	3.90	4.68	5.50	6.59	7.89	9.32
Soil +5% LFS	0.00	0.75	1.63	2.38	3.13	3.87	4.62	5.41	6.33	7.36	8.50

The effect of varying the dimensions of the stabilized zone, D and H, with 5% slag on settlement development are presented in Fig. 5. The diameter of the loaded zone remained constant at 1.5 m. It can be seen that the larger the width D and the depth H of the stabilized zone, the better the behavior of the stabilized zone. A larger area of higher stiffness (higher modulus E) was generated by increasing the stabilized area under the foundation, which provided a better response to settlement due to surface loading.

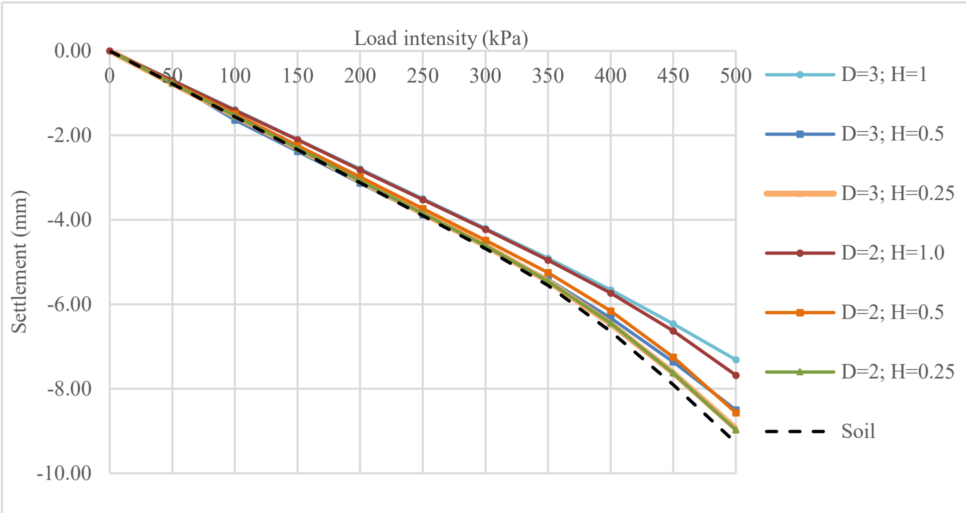

Fig.5. Evolution of settlement for different thicknesses and widths of the stabilized soil layer.

Fig. 6 shows the variation of settlement for a 3 m width of the slag stabilized zone. In this graph, the influence of the thickness of the stabilized zone for different diameters of the loading area can be observed. It was noticed that if the width of the stabilized zone and the diameter of the foundation remained constant, then in consequence greater settlement was observed, as the layer of treated soil was less thick, and the stiffness of that area was lower. On the other hand, it was found that the greater the width of the loaded zone under loading, at the same force, the less the settlement, due to the higher stress distributions.

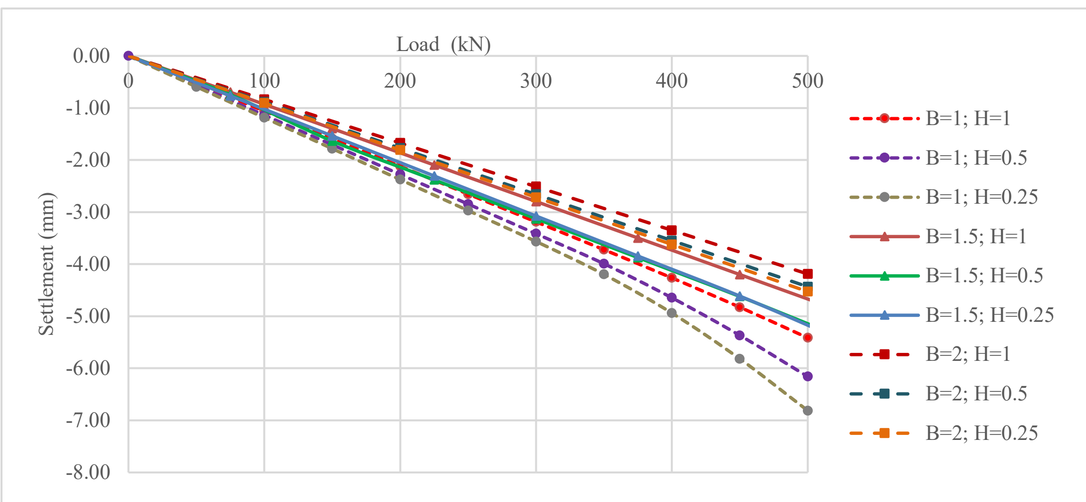

Fig.6. Evolution of settlement for different thicknesses of the stabilized soil layer and varying the diameter of the loaded zone.

The bar graph given in Fig. 7 shows the settlement improvement ratio (I_D) in a soil stabilized with 5% LFS where the depth and width of the stabilized zone were varied, for different loaded diameters under loading. A constant surcharge of 500 KPa was considered. I_D was calculated with Equation 2 [19], where S_p and S_{net} were the foundation settlements supported with stabilized soil and untreated soil respectively.

$$I_D = \frac{S_p - S_{net}}{S_{net}} \cdot 100 \quad (2)$$

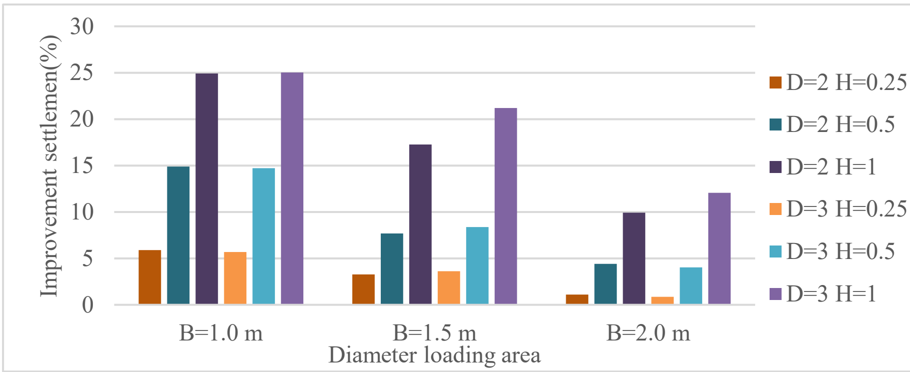

Fig. 7. Schematic representation of the finite element 2D model employed for the analysis

A stabilized zone with the same diameter, after increasing the thickness of the stabilized zone, resulted in less settlement, i.e., a greater improvement ratio was determined. On the other hand, increasing the width of the treated zone caused a slight improvement in settlement behavior, although it was not very significant. The increase in the diameter of the loading zone, considered as a uniformly distributed overload, implied a decrease in the improvement ratio, because the total load increased.

4. Conclusions

T The aim of this research work has been to ascertain the effect of dimensioning a stabilized zone on deformational behavior. The following conclusions are presented, in accordance with the experimental test results and the numerical analyses that have been described:

- The LFS-stabilized soil had a slightly lower plasticity index (PI) than the natural soil, resulting in a less cohesive soil which favored its placement.
- The results of the experimental tests demonstrated that the LFS mix increased the stiffness of the layered soil (UCS value increased, consequently the estimated elastic modulus of elasticity was higher) and improved the bearing capacity (CBR value improved considerably).
- Soil stabilized with LFS showed better settlement behavior than both untreated soil and lime stabilized soil, mainly due to its higher modulus of elasticity (E) and its higher shear strength values (c´ and Φ).
- An increase in the thickness of the stabilized area, generated less settlement. The shallowest area was the most affected by settlement, so the greater the stiffness of that area, the less deformation it will undergo.
- The stiffness of the stabilized areas moderately increased as their width increased. However, as the diameter of the loading zone widened, its effect was less favorable.
- Under the same forced load, larger loading area diameters resulted in less settlement, because the distributed load transmitted to the supporting soil was reduced in magnitude.

As a final conclusion, it may be affirmed that the use of LFS in soil stabilization is a suitable application for a sustainable circular economy in the construction sector, yielding a material with similar, and in some cases better, performance than the traditional lime-soil stabilization.

Acknowledgements

This research work was supported by the Spanish Ministry of Universities, MICINN, AEI, EU, ERDF and NextGenerationEU [grant numbers PID2020-113837RB-I00; 10.13039/501100011033; TED2021-129715B-I00]; the

Junta de Castilla y León (Regional Government) and ERDF [grant number UIC-231]; and the University of Burgos [grant number SUCONS, Y135.GI].

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