International Journal of Design & Nature and Ecodynamics
Vol. 19, No. 4, August, 2024, pp. 1151-1165
Journal homepage: http://iieta.org/journals/ijdne

Assessment of Soil Consolidation Techniques in Ecuador: Preloading and Wick Drains in the Exodo-Fertisa Project

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https://doi.org/10.18280/ijdne.190406

Received: 14 April 2024
Revised: 22 May 2024
Accepted: 5 June 2024
Available online: 28 August 2024

Keywords:
geotechnics, settlement, ground improvement, geophysics, wick drains and preloading

ABSTRACT

Consolidation settlements are a worldwide problem in different soil types, in which infrastructure works are built to develop a city or community. In the Ecuadorian coastal region, soft clay soils predominate, which generate excessive differential settlements, causing human losses and economic damage. This research aims to evaluate the consolidation of soft clays in Duran-Ecuador by applying preloading with wick drains and comparing it with geophysical tests (pre- and post-application) to analyse the consolidation rate efficiency. The methodology consisted of the following phases: (i) review of reference studies; (ii) analysis and interpretation of existing geotechnical data; (iii) technical evaluation of soil improvement with preloading and wick drains; and (iv) pre- and post-construction geophysical surveys (project serviceability). Soil consolidation analysis with no improvement was expected to require 81 months. At the same time, preloading and wick drains were achieved in 6 months, reducing the consolidation time by 90%. Moreover, settlements between 70-90 cm were excessively high according to the Ecuadorian Construction Standard, whereas settlements between 9-10 cm were expected by applying the improvement. Using geophysical tests, the improvement in the bearing capacity of the soil was determined through empirical correlations between the variation in electrical resistivity and soil void ratio. The combination of both methodologies (preloading and wick drains) in soft clay soils is an optimal solution for the reduction of consolidation time in the construction of a project.

1. INTRODUCTION

Soil is a complex porous material in which many phenomena co-occur [1]. Consolidation analysis of soft soils is one of the main problems in geotechnical engineering [2]. Consolidation is a process in which pore water pressure dissipates with the discharge of pore water from the soil and the effective stress increases under loading [3-5]. Soil consolidation characteristics vary with factors such as the stress history [6], mineral composition [7], water content [8] and loading time [9]. However, for organic or soft clayey soils, secondary compression can also be significant and must be considered [10]. The Tower of Pisa (Italy) [11], some existing buildings in Mexico City [12], and some buildings in Santos (Brazil) [13] are classic examples of structures built on soil subject to excessive consolidation settlement.

The construction of civil works is a challenge for engineers because of the characteristics of soft soils, such as low bearing capacity, low shear strength, and high compressibility [14]. Primary consolidation can take a long time because of the low permeability of clay soils [15]. Ground-improvement techniques are necessary to address and overcome these problems [16]. Techniques such as jet grouting use cement grout or volcanic ash to improve the strength and stiffness of soil [17, 18]. Granular columns are widely used in geotechnical engineering to reduce settlement, increase the bearing capacity, accelerate consolidation, and decrease liquefaction potential [19].

Improper treatment or the use of an inadequate technique on soft soil can lead to a series of practical engineering problems [20, 21]. Therefore, it is imperative to improve the soft soil conditions before using it as a foundation for any building. Preloading is a commonly used practical method to enhance soft soil conditions [22-24]. A case study in Zhuhai (China) used a conventional method of vacuum preloading and combined method of overburden preloading for the consolidation of clayey soils, obtaining a higher degree of consolidation and an increase in undrained shear strength (55.56% and 22.20%, respectively) [25]. Likewise, Xu et al. [26] conducted a case study in Tianjin (China), investigating the improvement of soft soil using vacuum preloading combined with overburden preloading. An improved settlement (approximately 66%) and consolidation degree (approximately 98%) were observed.

However, time is a major constraint in this method; therefore, it is commonly used with vertical drains to accelerate the consolidation process [27, 28]. Staged backfill preloading with vertical drains accelerates the consolidation process by decreasing the pore pressure [29] as well as the removal and replacement technique, which improves the bearing capacity of the soil and its resistance to shear stresses [30]. Ayeldeen et al. [31] and Bergado et al. [32] presented case studies of ground improvement (in northern Egypt and Bangkok, respectively) using Prefabricated Vertical Drainage (PVD) and overburden. This combination effectively reduces settlement, is a cost-effective solution, and is environmentally friendly.

The one-dimensional consolidation theory can be extended by including vertical drains, allowing drainage in different directions, such as radial, vertical, and horizontal [33]. One type of vertical drain used is wick drains, which are prefabricated geotextiles that reduce the draining distance of water in compressible clays, thereby significantly reducing the consolidation time [34]. This must be monitored and verified to determine the effectiveness of soil improvement techniques.

Several methods have been proposed for predicting the magnitude and rate of settlement of structures supported on soft soils and for monitoring ground improvement techniques [35, 36]. Numerous methods encompassing theoretical and analytical methods [37, 38], empirical formula methods [39, 40], and in-situ monitoring techniques [41-43] have been reported to study the characteristics of soil displacements. Ordinary in situ investigation methods, including soil drilling (for example, Standard Penetration Test (SPT) or Dynamic Penetration Tests (DPT)), were mainly carried out to study soil layers and soil mechanical parameters [44, 45]. However, few studies have adopted geophysical methods to verify soil improvement (e.g. electrical resistivity surveys) [32, 46].

Ecuador has diverse soils because its geographical regions share a heterogeneity of climatic and meteorological conditions [47]. Duran is in the coastal area, characterised by the predominance of soft clay soils [48]. These generate excessive settlements with low load levels given that their consolidation time is longer owing to their low permeability [49].

Owing to the exponential growth in the civil construction of warehouses or different industrial plants in Duran (Ecuador), it is necessary to ensure that soil improvement techniques are optimal, and to guarantee the monitoring of this improvement that allows the correct functioning of these civil works. There is a need to implement new methods for monitoring these improvements, in addition to being more economical than traditional methods (e.g. SPT, DPT, seismic dilatometer test (SDMT), and piezocone test (CPTu)).

Therefore, the following research question arises: What effects do the combination of preloading and wick drains in soft clay soil have on settlements in future civil works? The aim of this study was to evaluate the combination of preloading and wick drains in soft clays of the Exodus-Fertisa project (Duran-Ecuador) by performing geophysical and geotechnical field studies to verify soil improvement in civil works, the approach of guidelines, and the limitations of the analysed method.

2. STUDY AREA

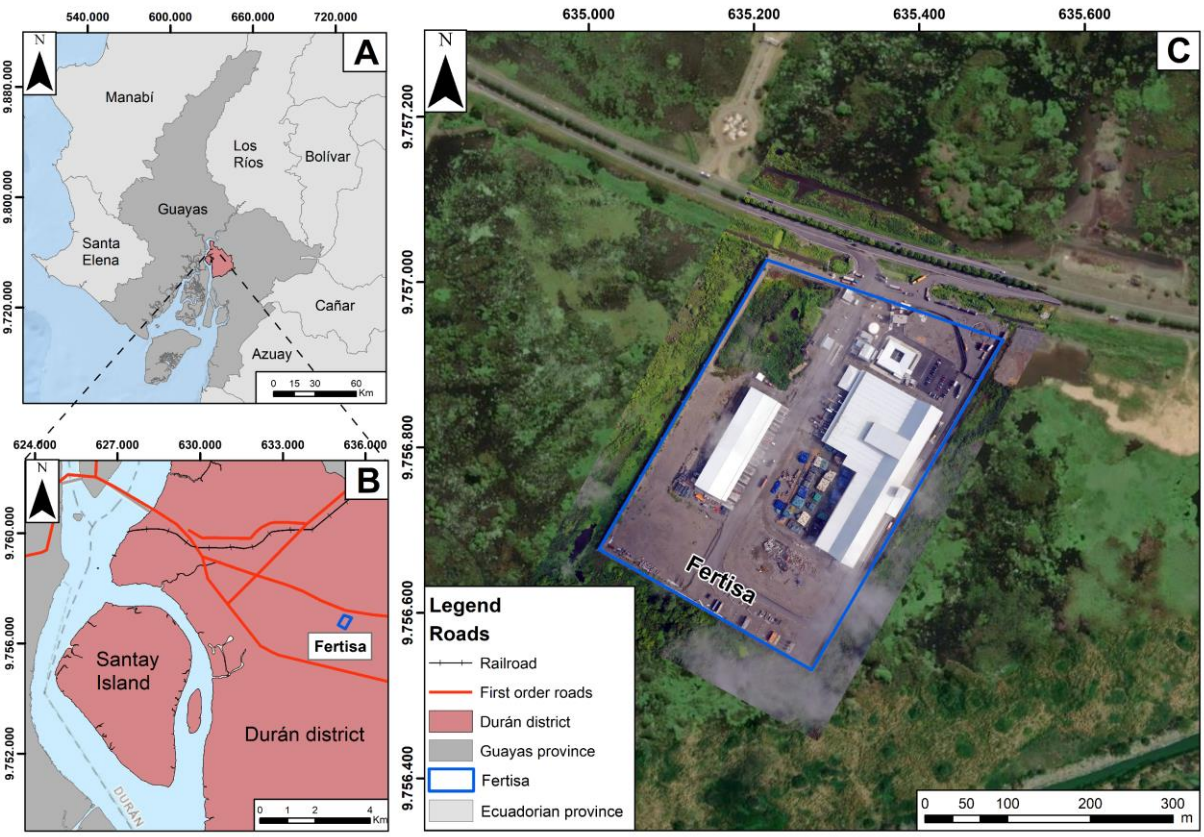


Figure 1. Geographical location of the study area (Duran-Guayas-Ecuador), with the delimitation of the Fertisa warehouse, where the preload with wick drains was placed

The Exodo-Fertisa project, located at km. 8 Duran-Boliche Road, represents a distribution and storage centre for agricultural products, such as fertilisers and herbicides, necessary for the development of crops, which enables a change in the productive matrix of farmers in the coastal region of Ecuador. This site includes our study area, the Fertisa Aquaculture Livestock Warehouse, which has an area of 5,070 m^2. The infrastructure is located on soft clay soil with water table depths ranging between 2.00 and 3.30 m (before the rainy season), which, combined with the terrain's irregular topography, allows for flood valleys (Figure 1). This is evident in the study area, with a Rivera Quality Index (RQI) of 30 for the Guayas River, indicating intense alteration and poor water quality [50]. The QBR is a commonly used indicator that responds significantly to environmental stressors and influences the river's physic-chemical quality [51].

The geotechnical conditions of the study area required settlement control within a specific period before construction of the project. As the duration of the consolidation process is a limiting factor, the densification of the ground through the preloading method (with compacted backfill) and wick drains, an effective method for short-term settlement control, was chosen [52].

3. MATERIALS AND METHODS

The methodology is based on the evaluation of the preload method and wick drains in a soft clay soil, applying geoelectrical (Geoelectric Tomography and Electromagnetic Survey), which correlates with geotechnical measurements, allows the assessment of the terrain enhancing, and therefore, the settlement mitigation and control. The following phases were defined: (i) review of reference studies; (ii) analysis and interpretation of existing geotechnical data; (iii) technical evaluation of soil improvement with preload and wick drains; and (iv) analytical study of pre- and post-geophysical data (Figure 2).

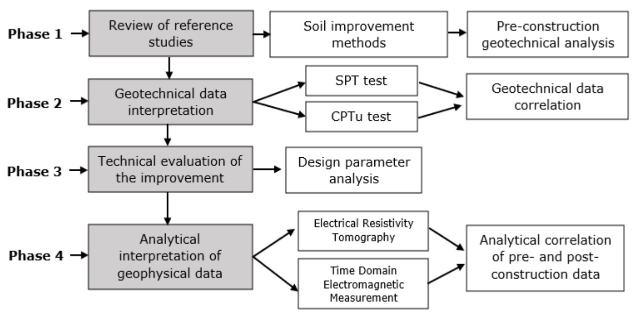


Figure 2. Diagram of the methodology used in this research, represented in two field phases and two research phases

SPT: Standard Penetration Test, CPTu: Cone Penetration Test with Pore Pressure Measurement.

3.1 Phase 1: Review of reference studies

In the first step, a secondary review was conducted using search engines (Google Scholar) and databases (Scopus) on soil improvement methods for soft clays. This soil type is very frequent along the Ecuadorian coast, mainly in sedimentary basins [53]. There are several solutions to the same problem [54, 55], but technical data were reviewed to properly select the improvement method to be used.

Geological and geotechnical studies were carried out before the construction of the warehouse to detect soft soils prone to significant settlements, according to experience in the sector. Based on previous experience in similar terrains [20], it was decided to use complementary preloading and vertical drains to determine the speed and efficiency of the consolidation process.

3.2 Phase 2: Geological and geotechnical data analysis

For the analysis of the current soil conditions, a geotechnical investigation was executed at depths ranging from 20, 50-40, 71 m in November 2018 and May 2020. In addition, mechanical borings were performed with thin-walled Shelby-type tubes, taking "undisturbed" samples every meter for cohesive soils and a Standard Penetration Test (SPT) every meter for sandy soils or stiff clays (Figure 3).

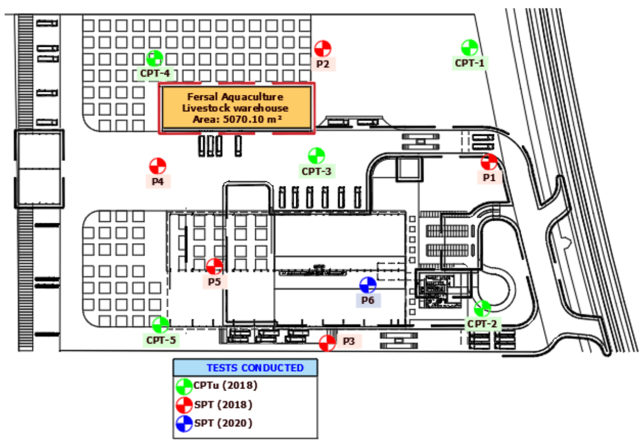


Figure 3. SPT and CPTu test locations performed pre-construction of the warehouse, within the study area

The SPT allows the soil type and stratigraphy to be identified by digging a sampler using a 63.5 kg hammer drill and counting the number of blows [56, 57]. Cone penetration tests with pore pressure measurement (CPTu) allowed a more accurate estimation of the in-situ consolidation rate. CPTu involves penetrating the cone probe into the existing ground, where the cone resistance (q_c), friction (f_s), and excess pore pressure (u_2) are continuously measured at a constant velocity [58, 59].

Once the geomechanical properties of the subsoil were determined using three-dimensional analysis programs, the consolidation settlement in the soft clay soil was estimated. The consolidation process over time depends on the degree of dissipation of the excess pore pressure generated by the applied backfill load on the ground surface. Settlement calculations were performed for both primary and secondary consolidation. The immediate settlements that occurred mainly during the backfilling and construction of the foundation of the structure were also analysed.

3.3 Phase 3: Technical evaluation of the improvement method

The selection of the soil improvement method in the study area depended mainly on the consolidation time. Owing to the short time required to execute the Exodus-Fertisa project, preloaded fill material was planned to meet the required density and settlement conditions. However, in this case study, it was desired to accelerate the settlement process (to start the construction of the Fertisa Warehouse); therefore, the placement and use of vertical drains were proposed to accelerate the consolidation process and improve the strength and stiffness of the clayey soils [60-64]. The implementation of the preloading and vertical drains is schematically presented in Figure 4.

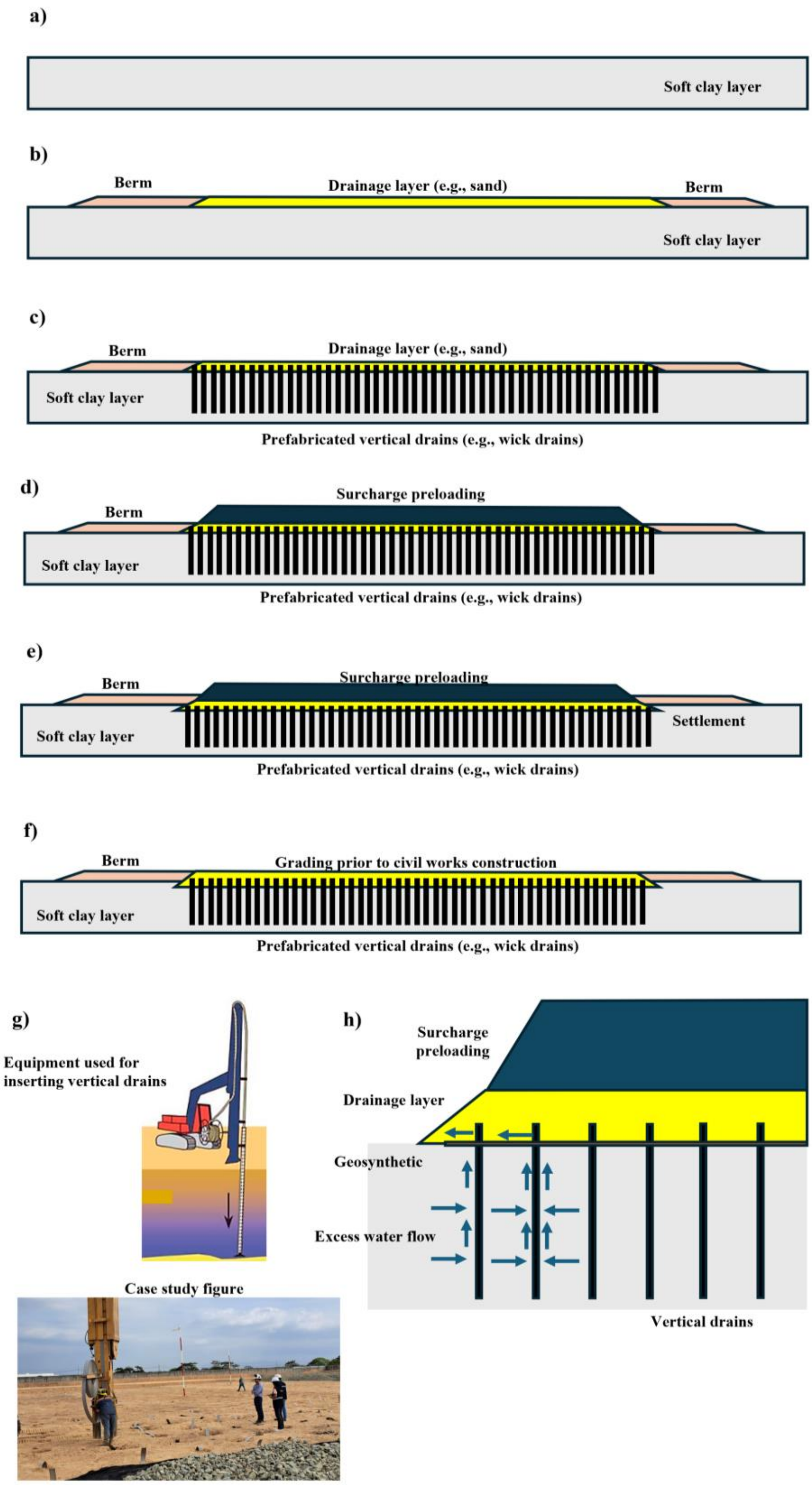
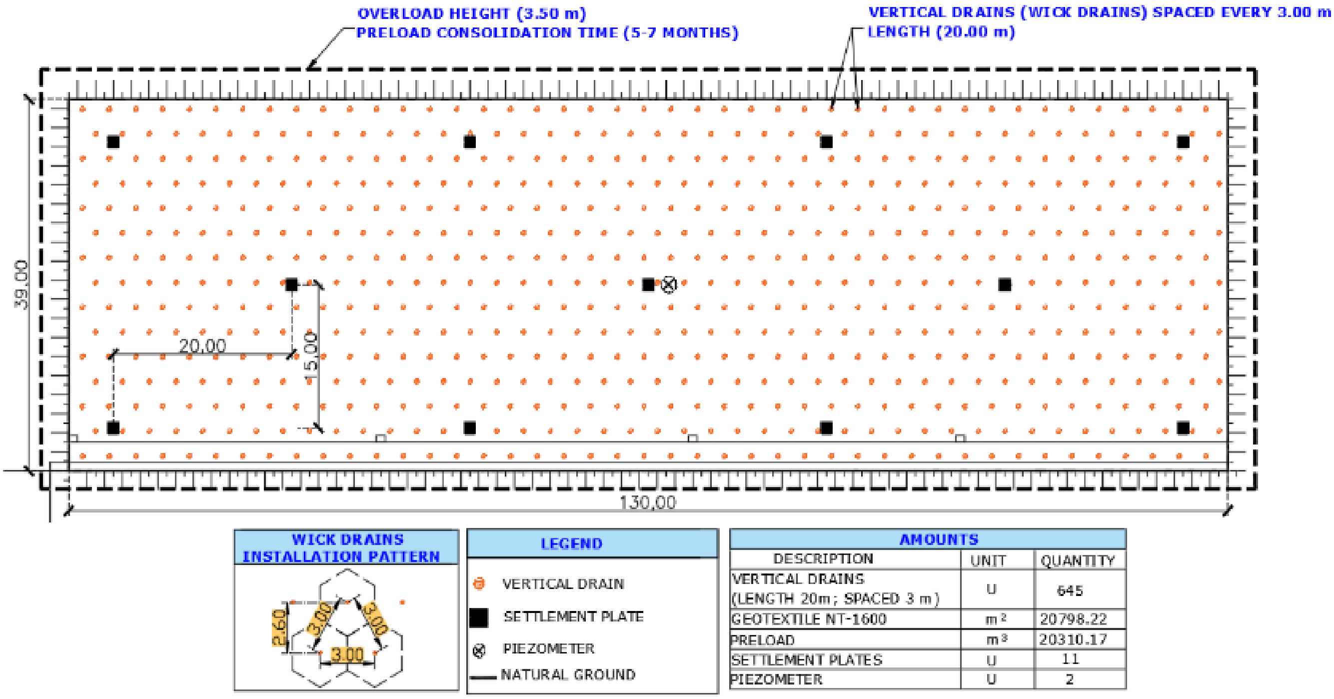


Figure 4. Diagram of the implementation process of the improvement techniques in the study area. a) Cleaning and levelling of the improvement area, b) Placement of the drainage layer, c) Installation of the prefabricated vertical drains, d) Placement of the preloading layer, e) Time to wait for settlements, f) Removal of the preloading layer and grading prior to construction of civil works, g) Installation of the drains by digging, h) Movement of water flow through the vertical drains to the drainage layer for evacuation



AMOUNTS		
DESCRIPTION	UNIT	QUANTITY
VERTICAL DRAINS (LENGTH 20m; SPACED 3 m)	U	645
GEOTEXTILE NT-1600	m²	20798.22
PRELOAD	m³	20310.17
SETTLEMENT PLATES	U	11
PIEZOMETER	U	2

Figure 5. Improvement technique implementation scheme (location of wick drains with triangular arrangement), monitoring devices (settlement plates and piezometers), and quantity table (Fertisa aquaculture livestock warehouse)
Modified from study [55]

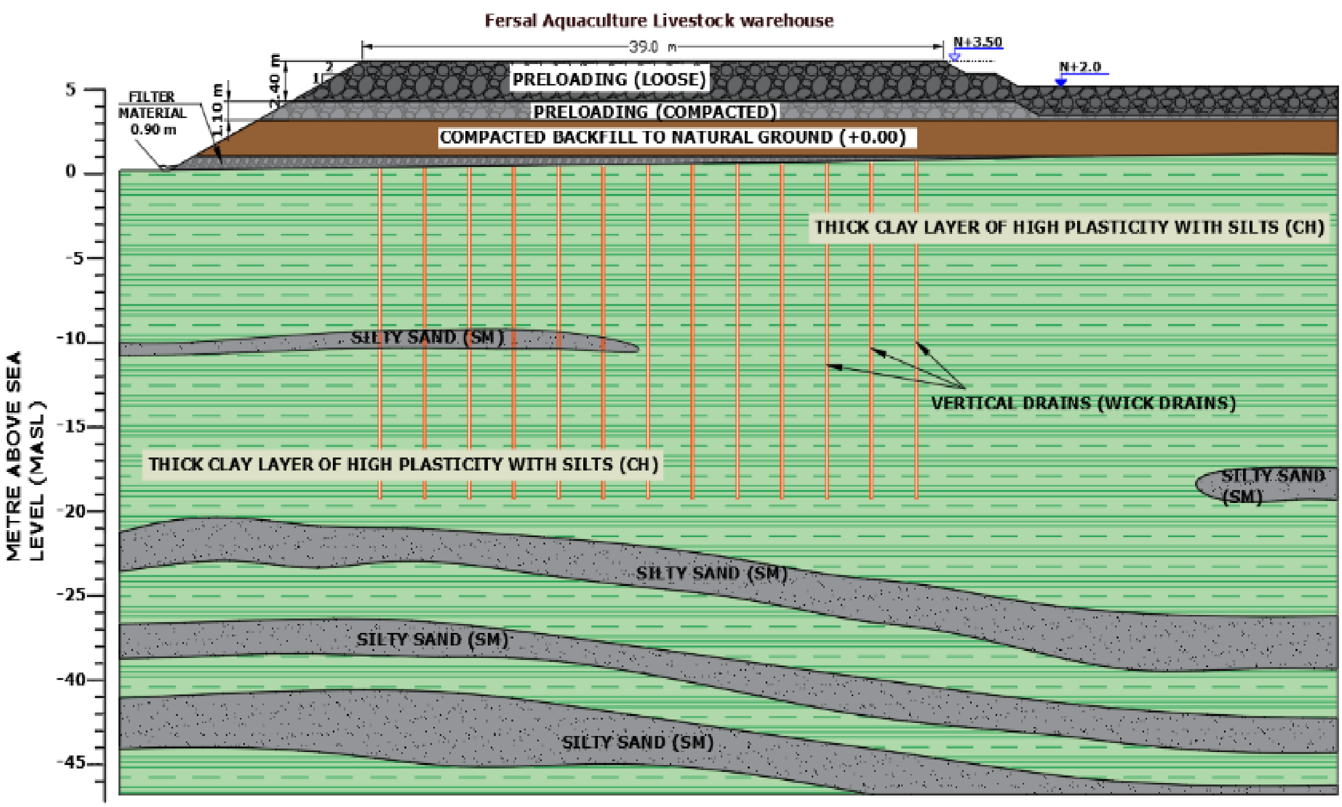


Figure 6. Schematic of preloading material used in the study area and materials obtained from SPT and CPTu tests
Modified from study [55]

The installation of prefabricated vertical drains (wick drains) was arranged in a triangular pattern (Figure 5), depending on the separation between the drains, depth, geotextile type, preload thickness, and soil permeability. Installing these vertical drains decreased the drainage distance within a compressible clay layer because drainage was facilitated horizontally and vertically, reducing the soil consolidation time. Another advantage of this method is that more economical shallow foundations will be used and not more expensive foundation methods, such as driven piles [65]. The depth that the vertical drains will reach varies according to the soil study because the soil reaches a sandy layer of medium to high density.

The preload height was determined as the contact stress was significantly higher than the weight of the structure corresponding to the Fertisa Warehouse. Therefore, it was decided to assume an even greater height so that the preloading backfill, once compacted, was at the level determined for the construction of the project. The scheme of overloads in the elevation under loose and compacted conditions is shown in Figure 6. With these techniques, the stress increase produces little settlement at the start of construction of the permanent structure. Reducing the spacing between vertical drains is not considered because this does not increase the permeability ratio [66].

3.4 Phase 4: Analytical correlation of pre- and post-construction geophysical data

The ERT geophysical tests were carried out using the Terrameter SAS-1000 electrical resistivity equipment and a tomograph, whereas the TDEM tests were conducted using the ABEM WalkTem 2 equipment. The data acquisition methodology for ERT was equidistant electrode spacing by applying the Wenner configuration. ERT data were processed using licenced software Res2DINV, version 4.10.20. For TDEM, the data were processed using licenced software Aarhus Spia, version 3.6.0.1.

Three geophysical tests were carried out (two Electrical Resistivity Tomography-ERT and a Time Domain Electromagnetic Measurement-TDEM), the locations of which are projected in Figure 7. ERT-01 is 100 m in length in the unimproved ground in the SE-NW direction, and ERT-02 is 80m in length in the NE-SW direction in areas close to the Fertisa aquaculture livestock warehouse in the Exodus-Fertisa project. TDEM-01 was carried out in an area without soil improvement, in a 40×40 m perimeter, reaching a depth of 106 m.

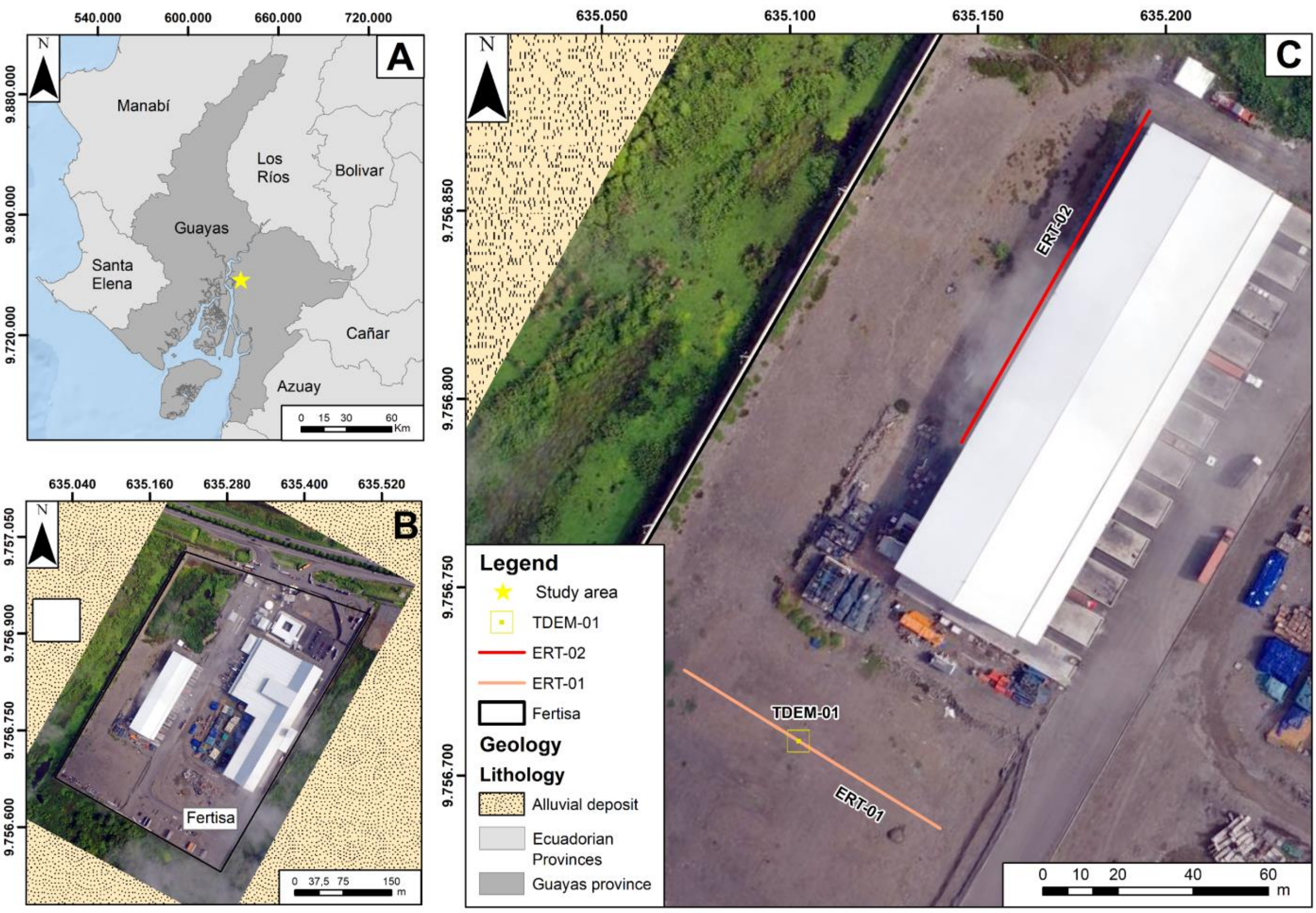


Figure 7. Location map of the geoelectric tests in the Exodus-Fertisa project, around the Fertisa livestock and aquaculture warehouse

With the geophysical data (electrical resistivities), geomechanical parameters are correlated through equations presented by several authors, allowing the interpretation and comparison of the expected results.

4. RESULTS

According to statistical data, 22% of lower settlements have been reported for other improvement methods using wick drains with preloading [67]. Therefore, the selection of an appropriate methodology must be based on a planning strategy for analysing soil behaviour [68].

The water table depth plays a pivotal role in both the interpretation of the geophysical test results and comparison of the effectiveness of the upgrading method. It has been reported at a depth of -2.42 m from the surface. During the rainy season, 38.6% of the area had a water table between 0.60-0.90 m, 11.68% between 0.30-0.60 m, and 18.2% between 0.00-0.30 m [69].

4.1 Geological and geotechnical characterisation

The study site predominantly comprises alluvial soils and marine clays formed by the estuarine deltaic complex and alluvial plain [70], belonging to the Holocene age as QTm Marine Terrace [71]. The Exodus-Fertisa project comprises intercalations of silty clays and sands, with the layer closest to the surface being an overconsolidated clay due to water table fluctuations in this 4.5 m thick layer.

Figure 6 shows the results of the field tests (SPT and CPTu), where the clay-silt and sand intercalations were verified. CPTu tests and soil borings are usually performed to characterise subsoil conditions [72]. Table 1 presents the results of the laboratory tests on the samples obtained in situ.

Table 1. Laboratory and in-situ test results (SPT and CPTu)

SPT	D (m)	Mat.	W (%)	FC (%)	LL (%)	PI (%)	N60
P2	20.5	CH	100	80	80	40	20
P4	20.5	CH	100	80	80	40	20
CPT	**H (m)**	**Mat.**	**BI**	**qc (MPa)**	**fs (MPa)**	**Mc (MPa)**	**Vs (m/s)**
CPT-3	21.8	CH	3	5	30	20	200
CPT-4	20.8	CH	3.3	5	30	20	200

Note: D: depth, Mat: material, CH: clay, W: moisture, FC: fines content, LL: liquid limit, PI: plasticity index, BI: behaviour index, qc: tip resistance, fs: shaft resistance, Mc: confined modulus, Vs: shear wave velocity.

Table 2. Description of projected backfill heights and overloads

Study Area	Project Level	Backfill Height (m)	Δσ Backfill (kPa)
Fertisa Warehouse	+1.20	3.20	60
	Δσ Overload (kPa)	**Δσ Total (kPa)**	**Improvement Implemented**
	60	120	Preload+wick drains

Table 3. Estimation of wick drains+preloading by comparison of improvement alternatives for decision making

Improvement Implemented	Consolidation Time	Characteristics
Preload	81 months	Compacted backfill
Preload+wick drains	5-8 months	Triangular arrangement 3×3 m, length 20 m
Improvement Implemented	**Expected Settlements**	**Total Stress**
Preload	0.70 to 0.90 m	100 kPa
Preload+wick drains	0.09 to 0.10 m	90 kPa

The mechanical properties of the subsoil obtained from the test data in Table 1 were analysed, focusing mainly on the characterisation of its undrained shear strength and its level of consolidation to assess the speed and magnitude of its settlement. A lower overconsolidation ratio (OCR) indicates higher settlement and longer consolidation times.

4.2 Analysis of settlements, overloads, and applied improvement

Owing to the preload and weight of the structure to be built, the overloads to which the soil was subjected were analysed. Table 2 lists the stresses transmitted (Δσ) by the preload and overload at the level of the project elevation.

According to the soil parameters and using Settle 2D, its response was analysed without any improvement, resulting in primary deformations of 0.40-0.60 m and 0.10 m for secondary compression. Finally, total settlements were estimated to be between 0.70-0.90 m, with a consolidation time of 81 months.

To reduce post-construction settlement by consolidation in the study area, the method of preloading with compacted backfill and the use of 20m long wick drains in a triangular 3×3 m arrangement was applied. The placement of a 3.20 m high compacted backfill made it possible to reach the project elevation for the Fertisa Livestock Aquaculture Warehouse. This procedure allows the consolidation rate to be 5-8 months, obtaining settlements of 0.09-0.10 m, which represents a 90% reduction in waiting time (Table 3).

4.3 Pre- and post-construction comparison of soil parameters

4.3.1 Correlation ERT-01 and TDEM-01 (Pre-Construction)

ERT-01, with a length of 80m and inter-electronic spacing of 5m, reached a depth of approximately 7 m and identified four layers of material (Figure 8(a)).

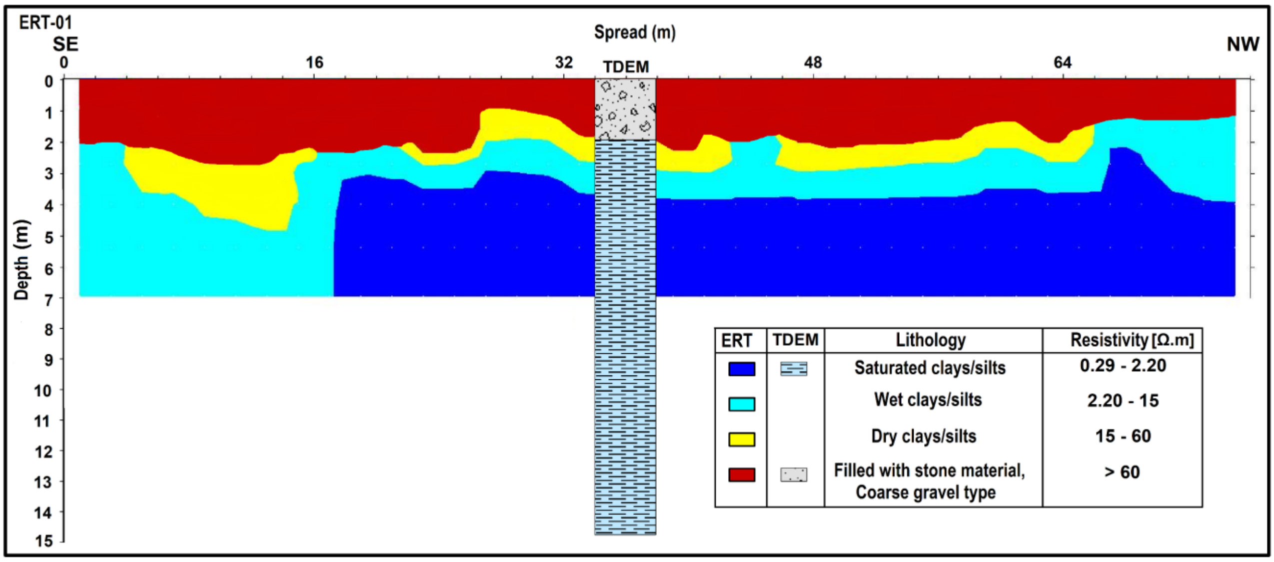
The first superficial layer with values greater than 60 Ω-m (red colour) represents a material with rock fragments corresponding to coarse gravel-type stone material filling with a variable depth along the profile of 1.60-2.00 m. Below this layer, the resistivity decreases to values between 15-60 Ω-m (yellow colour), with a layer of clay with dry to wet sand content and a thickness of approximately 1 m. To the northwest of the geoelectric profile, there are low resistivities of 15.0 to 2.2 Ω-m (light blue) corresponding to wet clays, whereas to the southeast (at a length of 16 m), at a depth greater than 4m, the lowest resistivity values were recorded (<2.2 Ω-m, blue colour), indicating a saturated clay.

In the central section of ERT-01, TDEM-01 (Figure 7) was performed, which verified the resistivity values obtained in the first 10m. In the TDEM-01, three layers of material were identified, reaching a depth of 106 m. The first layer coincides with the ERT-01, with a 1.90 m thick gravel-type stone fill material, an underlying layer of wet to saturated clays/silt of 12.60 m and the third layer with a thickness of 91.90 m, corresponding to a layer of saturated clays/silt.

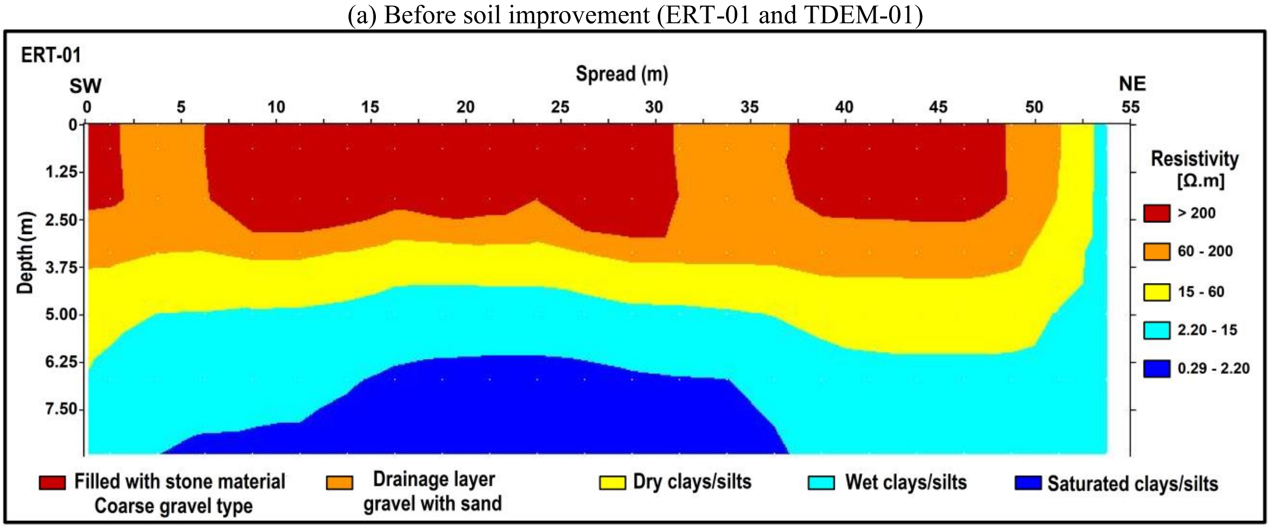
4.3.2 ERT-02 (Post-Construction)

ERT-02, with a length of 54 m and inter-electrode spacing of 5 m, reached a depth of 8.50 m (Figure 8(b)), differentiating five layers of materials.

The first layer, with an approximate thickness of 2.0 m (red colour), shows resistivities greater than 200 Ω-m, indicating a filling of coarse gravel-type stone material (gravel with silt and fine sand). The second orange-coloured layer has resistivities between 60-200 Ω-m, indicating the presence of gravel (drainage layer) with an approximate thickness of 1m. In the third yellow layer, resistivities between 15-60 Ω-m were recorded, with a thickness of 1 m, indicating the presence of silty clay. In the fourth layer, light blue in colour and 2m thick, resistivities range from 2.20-15.00 Ω-m, differentiating a clay with silt and high moisture content. Finally, a layer of very low resistivities (0.29-2.20 Ω-m) is observed, corresponding to saturated clays with silts.



(a) Before soil improvement (ERT-01 and TDEM-01)



(b) After soil improvement with preloading and wick drains

Figure 8. Soil stratigraphy through correlation of resistivity

Table 4. Equations relating geophysical parameters to geomechanical features

No.	Equation	Description	Author
1	$OCR = k_{OCR}\left(\frac{qt - \sigma_{vo}}{\sigma'_{vo}}\right)^{1.25}$	OCR=Overconsolidation ratio	Robertson [73]
2	$A_v = 0.92 - 0.97e^{-\frac{\rho}{109}}$	Av=Compressibility ratio	Fallah-Safari et al. [74]
3	$w = 0.18 - 0.23e^{-\frac{\rho}{6.65}}$	w=Water percentage	Fallah-Safari et al. [74]
4	$S = \frac{\Delta e}{1+e}H = \frac{\Delta\sigma_v}{1+\sigma_{v0}}\xi H$	S=Total settlement	Apuani et al. [75]
5	$C_c = \frac{\varepsilon(\Delta\sigma_v)}{\log\left(\frac{p}{p_0}\right)}$	Cc=Compression index	Bryson [76]
6	$\frac{\Delta\sigma}{1+\sigma v} = 3.233\frac{\Delta e}{1+e} + 0.023$	$\frac{\Delta\sigma}{1+\sigma v}$ Passed maximum pressure	Kibria et al. [77]

4.3.3 Analytical interpretation of geophysical data

The systematic review related to soil behaviour highlights the equations, which allow correlating geophysical parameters with geomechanical characteristics (Table 4).

Eq. (1) was employed to calculate the OCR values based on the consolidation tests of the samples tested in the SPT test, thereby verifying the soil properties. By correlating the resistivities of the geophysical tests, the void ratio was obtained, a parameter that provides a more comprehensive understanding of the soil's consolidation process over time (Table 5).

Table 5. OCR and e_0 values calculated from empirical equations

Soil Type	Layer	Thickness (m)	Geotechnical Evaluations		Empirical Correlations	
			e_0	OCR	e_0	OCR
Clay with silt present	1era	4.0	2.0	1.5	2.6	1.4
	2nda	1.4	1.8	1.5	1.0	1.4
	3era	2.0	2.5	5.0	1.4	5.0
	4ta	4.0	1.0	5.0	2.0	5.0

Subsequently, settlements were calculated based on the change in the void ratio, using Eqs. (2), (3) [74], and (6) [77]; likewise, soil deformations were evaluated using the factor ξ, which relates the conductivity and void ratio through Eqs. (4) [75] and (5) [76] (Table 6).

Table 6. Values and comparison of total settlements, calculated from empirical equations

Empirical Correlations		Geotechnical Evaluations	Difference (%)
Equation	Settlement (m)	Settlement (m)	
Fallah-Safari et al. [74]	0.79	0.90	12.20
Apuani et al. [75]	0.45		50.00
Bryson [76]	0.81		10.00
Kibria et al. [77]	0.52		42.20

5. DISCUSSION

The settlements calculated from geotechnical parameters (Settle 2D) were considerably high, between 0.70-0.90 m, consolidating in 81 months without any improvement [55]. As a storage warehouse, the project had to be constructed within the shortest possible time; therefore, accelerated consolidation was required. The improvement technique was the use of vertical drains (wick drains) and a preload, which, by removing the water and air in the clay layers, reduced the consolidation time (5-6 months), resulting in settlements of 0.09-0.10 m, reducing deformations by approximately 90%. In the Port of Cadiz, wick drains, and a preload of 5.5-12.0 m were used for six months, where settlement measurements of 0.57 m were obtained in slabs, which after removal of the overload were reduced to 0.52 m (9% of the original settlement) [78]. In the Main Building of the Canadian Port of Entry in Windsor, a preloading procedure with wick drains was performed, where settlements of up to 1.05 m were observed with a consolidation time of 12 months before the removal of the overburden, and a gain of between 40% and 100% of undrained shear strength was achieved [67]. On the other hand, in a shopping centre in Florida on fills of anthropogenic origin and residual soils, a settlement of between 0.15-0.25 m was expected, a wick drains fill, and a rock fill was chosen, whose consolidation process was completed in 3 months, reducing settlements to 0.03-0.19 m [52].

Geophysical tests allow quick and cost-effective exploration of the soil, and the stratigraphy of the soil can be determined to a certain extent using resistivity values [79, 80]. Geophysical techniques that measure electrical resistivity are susceptible to water or voids [75, 81]; therefore, electrical conductivity decreases with increasing pressure, improving consolidation owing to the dissipation of pore water. In a study in the Mexico Valley basin, where a 2.8 m preload and prefabricated vertical drains (wick drains) were used, piezometers were used to measure the dissipation of excess pore water pressure in this 53-month test [82]; almost total dissipation was verified at the end of the period.

The pre- and post-construction geophysical tests showed a representative increase in soil resistivity, differentiating four main layers of varying thicknesses. The predominance of soft saturated clays with very low resistivities, between 0.29 and 60.00 Ω-m, was observed in the natural soil before the construction of the project. Likewise, the soil characteristics were modified by executing the soil improvement with wick drains, resulting in higher resistivities between 0.29 and 200.00 Ω-m, implying greater soil stiffness due to the vertical drains and preloading. In comparison to a case study in Jiangsu, China, patented Electrically Conductive Wick Drains (ECWD) have been presented which, with a resistivity of less than 10^{-3} Ω-m, manage to lower the moisture content from 62% to 39% in soft clays in 36 days [83].

The depth of the water table depends on the season in which the in-situ tests are analysed, considering that the study area is prone to temporary flooding during the rainy season [84, 85]. Therefore, hydrological analysis should be conducted to determine the historical water table elevation and establish the lengths and elevations to design the vertical drain arrangement. In a project carried out in Colombia, a comparison was made between a scale model of vertical drains and their finite element software model to establish stresses and deformations, which requires an adequate estimation of the water table, proving that the consolidation time is 84% less using wick drains [86-88].

From the analytical evaluation of the geotechnical and geophysical tests using empirical correlations, it was found that the OCR and void ratio data calculated from the SPT, and CPTu tests are related to the data obtained from the geophysical tests (ERT and TDEM) [87]. The void ratio is the primary factor determining the settlement, which is dependent on the electrical resistivity [88, 89]. In contrast, inverse resistivity shows a bijective correlation with water content [90], a secondary factor [91]. A project in Indonesia on the Trans-Java highway showed that prefabricated vertical drains accelerate the consolidation rate by up to 90% within one year, as proven by geoelectrical resistivity investigations similar to this study [92].

The settlements calculated by geotechnical testing are close to those obtained empirically using formulas correlating geophysical (resistivity) and geotechnical (void ratio) parameters, as demonstrated by the values determined for the upgrading carried out in the Exodus-Fertisa project. However, in a project in Alexandria (Egypt), where 6.5 m preload and wick drains were used, a settlement of 0.74 m was reached. However, the recovery after removal of the preload was 0.72 m (i.e. a recovery of 3% of the original settlement) [93].

Wick drains are functional if the drainage layer is above the water table to enable drainage. The consolidation time in clay layers depends on several factors such as the distance between drains, driving depth, preload thickness, and stratigraphic characteristics. Fine sand intercalations are present in the ground, facilitating water drainage not only radially and horizontally but also vertically, favouring the design and application of the method.

Prefabricated vertical drains (PVD), such as wick drains, are functional as long as the drainage layer is above the water table, so that water drains to the surface. The consolidation time in clay strata depends on several factors such as the distance between drains, driving depth, preload thickness, and stratigraphic characteristics. Fine sand intercalations are present in the soil, facilitating water drainage not only radially and horizontally but also vertically, favouring the design and application of the method. Another variable to consider is the size of some fine particles that can be easily filtered through the filter, diminishing the draining effect of PVD. Wang et al. [94] tested different filter types to determine the most optimal filter type that yields better results in terms of the degree of vacuum, settling, pore water pressure, and water content. Likewise, Qin et al. [95] analysed the variables of the radius of influence and the appropriate depth that the PVD should have for the optimal dissipation of excess pore pressures.

Combining soil improvement techniques, preloading plus prefabricated vertical drains helps to increase the settlement (in both primary and secondary) and consolidation rate of soft soils. In addition, in the different soil layers, there was a significant decrease in water content, an increase in undrained shear strength, and a slight increase in lateral displacement (in deeper soils). As in the case study at Bangkok airport [96], they used a finite element model to verify the increase in soil characteristics by applying surcharge preloading and varying the length of the PVDs. Likewise, in the Mae Moh mine (Thailand), PVDs were used to recover dredged soils, decrease water content, and increase the undrained shear strength [97].

6. CONCLUSIONS

Within the Exodus-Fertisa project (Duran-Ecuador), a combination of preloading was applied using backfill (3.20 m high) and vertical drains (20m long wick drains in a triangular arrangement), which accelerated the consolidation time and magnitude of settlements in soft clays. Using geophysical survey campaigns (two TGE and one TDEM), it was verified that the applied improvement technique controlled the settlements (9-10 cm) and the project's water table.

Preloading (by backfilling) and vertical drains (wick drains) drastically reduced the settlement time by reducing the excess pore pressure in the soil. These soft clay improvement techniques allowed for a 90% reduction in consolidation time (5-8 months) in this project, in addition to the expected settlements (0.09-0.10 m), reducing them by more than 88%. The degree of consolidation was verified using pre- and post-geophysical measurements according to the changes in soil resistivity values. Figure 8 shows a layer of dry clays/silt (15-60 Ω-m) of approximately 0.50 m, whereas Figure 7 shows a thickness between 1.00-1.25 m.

In soil improvement techniques, constant monitoring is required to control the actual settlement performance and consolidation rates achieved by measuring the pore pressure dissipation over time, such as piezometers and settlement plates. These should be evaluated each time to ensure that the soil consolidates according to the planned time. This was verified by the calculated geophysical values (resistivities) and correlated with geotechnical values (void ratios).

Studying the correlations between the electrical parameter values obtained from geophysical testing is important because they present a less time-consuming alternative to conventional sampling methods. Correlations between electrical resistivity and consolidation-related parameters, such as void ratio, prove to be demanding because voids in the soil can be caused by air or water, and air acts as an insulator. In contrast, water contains ionised mineral salts that enhance the electrical conductivity of soil.

Through TDEM and TGE carried out once the Fertisa Aquaculture and Livestock warehouse was built, four predominant soil layers were differentiated on the site: clays of high plasticity with silt presence. These were compared with the parameters of the pre-construction soil, and an increase in resistivity was observed, which indicates that the consolidation process of the soil improved, resulting in an efficient preloading method with wick drains.

Therefore, using preloads and wick drains with the subsequent use of shallow foundations is a good option for projects with a predominance of soft clays that require almost immediate construction. However, despite improving the soil parameters, this method has limitations. Its effectiveness depends on factors that must be analysed and calculated analytically, such as the incidence of the depth of the water table, depth of installation of wick drains, distance between geosynthetics, thickness of preloading, and location of the drainage layer.

Applying geophysical survey methods (e.g. TDEM or TGE) allowed us to determine the increase in the consolidation rate of clayey soil of the Exodus-Fertisa project. Compared to traditional in situ methods (e.g. SPT, CPT, and DMT), geophysical methods will guarantee project economy (a reduction of almost half of the monitoring budget); they will also improve the construction time of civil works (e.g. reduction in the delivery of results on the degree of soil consolidation and soil monitoring). However, geophysical methods must be used for constant monitoring during ground improvement.

ACKNOWLEDGEMENTS

To the Master in Geotechnics (FICT-ESPOL) for all the knowledge imparted and academic excellence. To the company Fertisa for authorising the use of the Exodus-Fertisa Project data and for permission to carry out field surveys within their facilities. The CIPAT-ESPOL provides logistical support, personnel, and geophysical equipment for field research. This work was supported by the research project "Registration of geological sites of interest in Ecuador for sustainable development strategies", Code CIPAT-004-2024 of the ESPOL Polytechnic University.

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NOMENCLATURE

m	Meters
m^2	Square meters
RQI	Rivera Quality Index
SPT	Standard Penetration Test
DPT	Dynamic Penetration Tests
SDMT	Seismic Dilatometer Test
CPTu	Piezocone Penetration Test
ERT	Electrical Resistivity Tomography
TDEM	Time Domain Electromagnetic Measurement
SE	Southeast
NW	Northwest
NE	Northeast
SW	Southwest
Ω-m	Ohm per metre
OCR	Overconsolidation Ratio
$\Delta\sigma$	Stress transmitted
Av	Compressibility ratio
w	Water percentage
S	Total settlement
Cc	Compression index
e_0	Void ratio