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Assessment of the Settlement and Horizontal Displacement of Test Embankments with Preloading, Drains, and Vacuum in the Former Texcoco Lake, Mexico

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Abstract. In this paper, the settlement and horizontal displacement of four test embankments (TEs) built in the former Texcoco Lake are evaluated. The embankments are part of the New Mexico City International Airport (NAICM) project and were constructed to study the effects of different soil improvement techniques based on surcharge preloading with (a) sand drains and prefabricated vertical drains (PVDs), (b) PVDs and drain-to-drain vacuum pressure, and (c) PVDs, vacuum pressure, and an airtight membrane. Their behavior is compared with that of an unimproved reference embankment. The site conditions are described, and the geometric and construction characteristics of each embankment are presented. A monitoring period of 360 days after the start of construction is discussed. In addition, the degree of consolidation in each trial embankment is calculated based on *in situ* records from settlement plates. Finally, the effectiveness of each soil improvement technique is analyzed, and some concluding comments are provided.

Keywords. Test embankment, lateral displacement, settlement, vacuum consolidation.

1. Introduction

Many infrastructure projects have been damaged by the settlement and lateral movement of underlying soft clay, which are mainly due to inadequate soil improvement prior to construction [6]. Soil stabilization using improvement techniques prevents inadmissible behavior in buildings, such as differential settlement or tilting, even collapses in extreme cases.

Due to the construction of the New Mexico City International Airport (NAICM, in Spanish abbreviation) in the area of former Texcoco Lake and especially the infrastructure on the airport side (such as runways, platforms, and taxiways), it was

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necessary to build test embankments (TEs) to evaluate different solutions for the foundations of these structures.

In soft soils, such as clays, it is possible to induce consolidation using the surcharge preloading technique. With surcharge preloading, which uses only earth material, the soil may take a very long time to settle. An effective method that decreases the time required for primary consolidation is the use of vertical drains [12]. The purpose of these drains is to provide a shorter distance for water to travel and thereby accelerate the consolidation process [3]. In addition, if the cost of the earth material for preloading is high or if there is a shortage, preloading using vacuum pressure is a viable alternative [2, 8].

This paper evaluates the evolution of settlement and lateral displacement over the course of one year after the construction of four TEs located at the NAICM site. The degrees of consolidation achieved with the different improvement techniques implemented are also estimated. In the end, some concluding comments about their behavior are given.

2. Geotechnical characteristics of the site

Figure 1 shows the results of geotechnical surveys conducted at the study site. The water content (w %) of altered soil samples obtained from a standard penetration test (SPT) with a tip resistance (q_c) was determined at different depths by means of a cone penetration test (CPTu). Based on geotechnical exploration, it has been determined that the stratigraphic profile of the area of interest is composed of the following strata [4]:

- *Surface Crust (SC)*. The SC has an approximate thickness of 1.0 m and consists of light brown clay with some sand. Its average water content is approximately w=86%, and its volumetric weight is γ=14.5 kN/m^3. The water table is located 1.0 m below the natural ground level (NGL).
- *Upper Clayey Formation (UCF)*. The UCF is composed of gray-green clay with high compressibility (HC) and a very soft consistency that includes ash and sand lenses. It has an average water content w=217% and a volumetric weight γ=12 kN/m^3. This stratum is located between 1.0 and 30.6 m deep.
- *Hard Layer (HL)*. The HL is composed of a greenish-gray sandy-silty material (SM) with a hard consistency, volumetric weight γ=18 kN/m^3, and average water content w=48%. It is located between 30.6 and 32.6 m deep.
- *Lower Clayey Formation (LCF)*. The LCF is composed of a greenish-brown clay with intercalations of gray clay with hight plasticity and high carbonate content. Its average water content is w=140%, and its volumetric weight is γ=13 kN/m^3. It is located from 32.6 to 43.8 m deep.
- *Deep Deposits (DD)*. These are located between 43.8 and 50 m deep and are composed of sandy-silty soil. Their volumetric weight is γ=19 kN/m^3.

3. Characteristics of the TEs

The four TEs described in this paper, TE-1 to TE-4, are located within a test polygon at the south side of runway 3 of the NAICM (Figure 2) whose exact location is illustrated in Figure 3. Their general characteristics are described below:

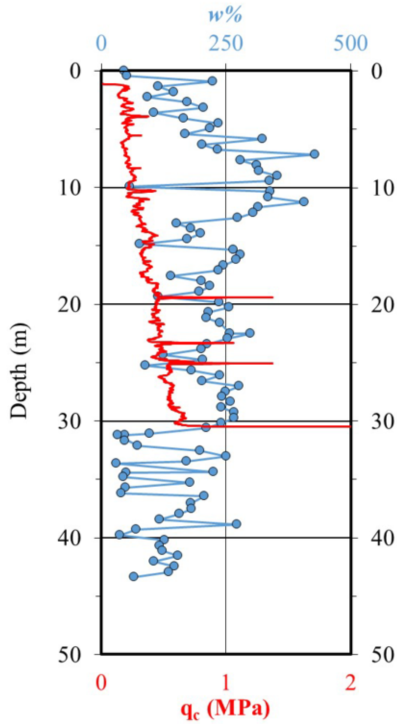

Figure 1. Water content records and tip resistance at the site.

- ***TE-1: Reference embankment.*** This embankment does not have any soil improvement; its dimensions are 60×60 m with a maximum height of 2.1 m at the center (Figure 4a). It is composed of three layers: (a) *tezontle* with volumetric weight γ=12 kN/m^3 that is 1.0 m thick, (b) a 0.5-m-thick sandy-silty layer (γ=17 kN/m^3), and (c) a third layer of pavement that is 0.6 m thick at the surface. This embankment transmits a pressure of 37.4 kPa.
- ***TE-2: Embankment with surcharge preloading combined with prefabricated vertical drains (PVDs) and sand drains (SDs).*** Its dimensions are 30×60 m, and it is composed of a 1-m-thick layer of *tezontle* (γ=11 kN/m^3) that underlies a 1.8-m-thick silty-sandy layer (γ=18 kN/m^3) in the central part of the embankment. The preload is 2.8 m high at the center and uses two soil improvement techniques: the eastern half has PVDs, and the western half has SDs (Figure 4b). The PVDs are placed at a depth of 30 m below the NGL in a triangular arrangement with separation S=2.0 m. The SDs have a diameter of 0.4 m and are placed at a depth of 27 m below the NGL with a triangular arrangement and S=3.0 m. This embankment transmits a pressure of 43.4 kPa.
- ***TE-3: Embankment with surcharge preloading, PVDs, and drain-to-drain vacuum pressure.*** Its dimensions are 50×70 m, and it consists of four layers of *tezontle* (γ=11.25 kN/m^3), with a total height of 2.0 m (Figure 4c). Vacuum pressure was applied for 6 months to the UCF through flexible horizontal pipes connected to the PVDs. A total of 3,045 PVDs with star-type cross-

sections (called *star drains*) 30 mm in diameter were placed in a triangular arrangement with S=1.2 m and placed at a depth of 28 m below the NGL. Vacuum pressure was generated by six pumps located at the southern end of the embankment (outside the platform) that were connected directly to the flexible horizontal pipes. The embankment transmits a pressure of 22.5 kPa, plus an average pressure caused by the vacuum that was equivalent to -58 kPa [4, 9,10].

- ***TE-4: Embankment with surcharge preloading, PVDs, vacuum pressure, and an airtight membrane.*** Its dimensions are 50×70 m, and it consists of four layers of *tezontle* with different volumetric weights (γ_1=γ_2=13.7, γ_3=19, and γ_4=11 kN/m^3), with a total height of 2.0 m (Figure 4d). The first two layers are covered by an airtight membrane 1.5 mm thick, which is anchored in a trench located on the perimeter of the embankment. Under the membrane (immersed in the *tezontle*), 43 horizontal drains are installed, and within the subsoil, 2,808 wick-type PVDs are placed in a triangular arrangement with S=1.2 m and placed at a depth of 27 m below the NGL. The PVDs are not connected to horizontal drains. Vacuum pressure was applied for 6 months and was generated by two pumps, one on the south side and one on the north side of the embankment (outside the platform). The pumps were connected directly to the horizontal drains of the system. The embankment transmits a pressure of 27.1 kPa, plus an average pressure caused by the vacuum that was equivalent to -63 kPa [5].

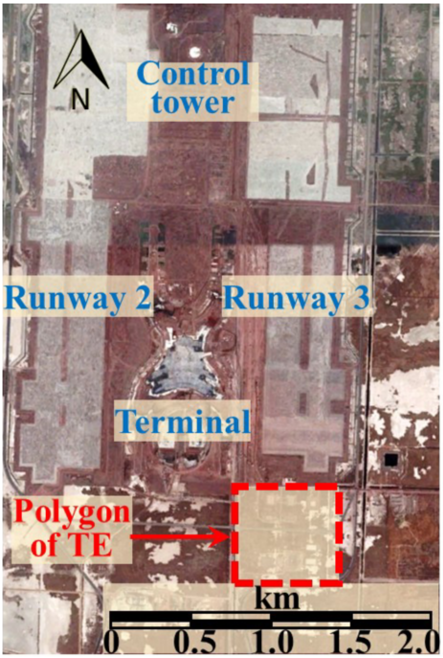

Figure 2. Location of the polygon of TEs in the NAICM.

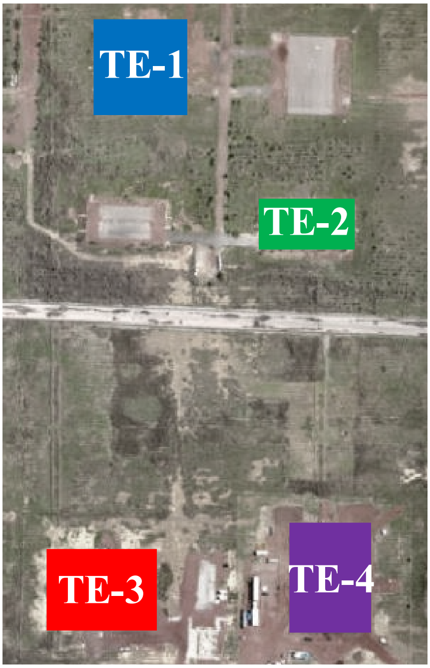

Figure 3. Locations of TE-1 to TE-4 within the polygon of TEs.

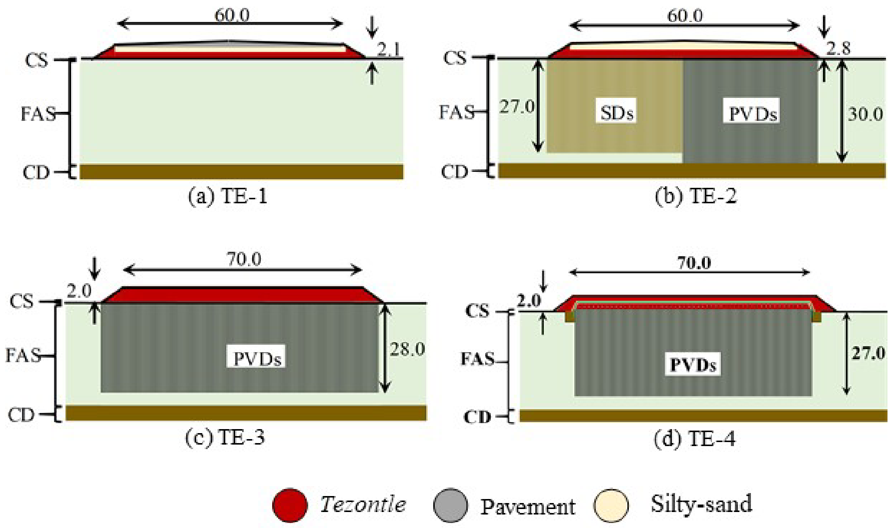

Figure 4. Characteristics of test embankments TE-1 to TE-4.

4. Geotechnical instrumentation

In the TEs, a variety of geotechnical instruments were installed to analyze the behavior of each of the improvement techniques. The evolution of the settlement and lateral displacement over time was evaluated using *in situ* records of horizontal inclinometers (HIs), settlement plates (SPs), and vertical inclinometers (VIs) as explained in the following paragraphs.

5. Assessment of settlements

Figure 5 shows the dimensions (plan view), the *in situ* measurement points, the settlement measurements, and the estimated settlement rate per day in TE-1 to TE-4 for 360 days (the square symbol) from the onset of construction. The settlement in the center of platforms TE-1 to TE-3 was measured using HIs, and for TE-4, the settlement was measured with an SP. Day zero (0) indicates the beginning of construction.

The construction times (the circular symbols) were 62, 63, 127, and 175 days for TE-1 to TE-4, respectively. For TE-3 and TE-4, the first settlement measurements (the diamond-shaped symbols) were made on days 80 and 23, respectively; similarly, the beginning and end of the application of vacuum pressure are indicated by triangular and star-shaped symbols, respectively. In addition, in TE-4, due to the pump shutdown protocol, vacuum pressure was retained inside the membrane keeping the valves closed for 15 days after the vacuum was turned off. With the above, it was possible to observe the effect of the remaining vacuum pressure in the event of an electric power failure. The pentagonal symbol indicates when the valves were opened.

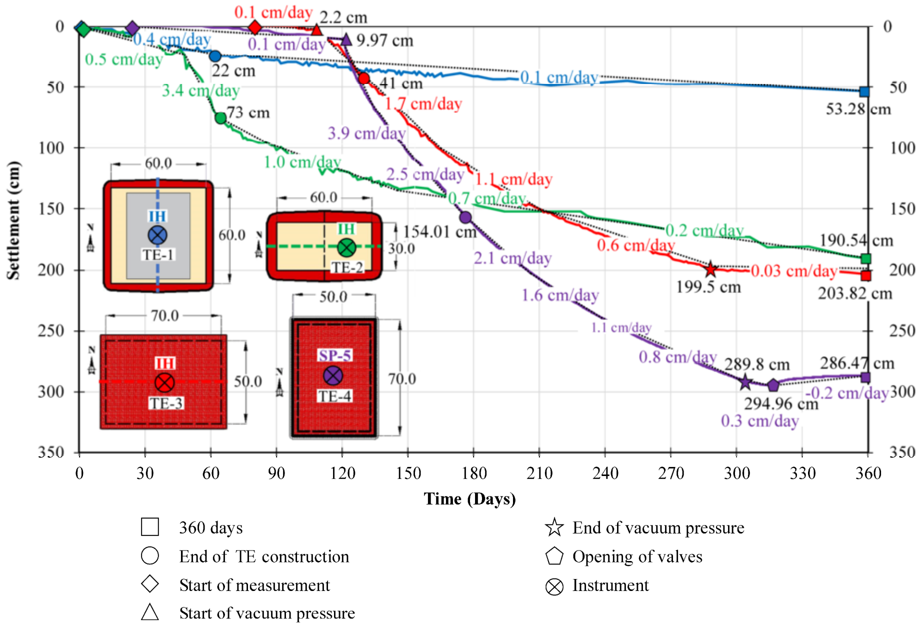

Figure 5. Settlement and settlement rate per day in TE-1 to TE-4.

5.1. Settlement measurements

After 360 days of monitoring, a clear difference can be seen in the evolution of the settlement for each soil improvement technique (Table 1). TE-2 developed a total settlement of 190.5 cm, which was 3.6 times that observed for TE-1 (53.2 cm). TE-3 and TE-4 settled by 203.8 cm and 286.4 cm, respectively, which were 3.8 and 5.4 times that observed for TE-1.

The settlement recorded at the end of the vacuum application (6 months) for TE-4 was 45% higher than that for TE-3. Due to the pump shutdown protocol, when the valves were opened and the remaining vacuum pressure in TE-4 was released, an expansion of approximately 3% (8.49 cm) of the maximum settlement reached (295 cm on day 316) was observed from day 316 to 360.

Table 1. Settlements in the test embankments.

Embankment	$S_{360days}$ (cm)	V_{max} (cm/day)	T_{Vmax} (days)	V_{avg}(cm/day)
TE-1	53.3	0.1	298	0.1
TE-2	190.5	3.4	15	0.5
TE-3	203.8	1.7	57	0.7
TE-4	286.5	3.9	14	0.8

$S_{360days}$ = Settlement at 360 days, V_{max} = Maximum settlement rate, T_{Vmax} = Duration of the maximum settlement rate, V_{avg} = Average settlement rate (weighted average).

5.2. Settlement rates

The magnitude and the settlement rate facilitated by soil improvement techniques have been studied based on the compressibility, preconsolidation stress, and permeability reached after soil stabilization [11]. Recent studies have focused on assessing the relationship between the settlement rate observed during surcharge preloading in constant increments and settlement following embankment construction [14].

Figure 5 shows that the settlement rate recorded during embankment construction is influenced mainly by the pressure exerted on the soil by its constituent materials. The settlement rates of the embankments with vacuum pressure, TE-3 and TE-4, are similar even before applying the vacuum pressure because both have 2 m height of *tezontle*. In contrast, TE-1 and TE-2 exhibit different settlement rates at the end of construction because they have different heights and materials, but mainly because TE-2 has vertical drains that facilitate the expulsion of groundwater and thereby accelerate consolidation settlement. In contrast, the maximum settlement rate for TE-3 and TE-4 is maintained for a short time and gradually tends to decrease as consolidation progresses. The average settlement rate (V_{avg}, Table 1) of TE-3 and TE-4 is up to 60% greater than that of TE-2 and up to 800% that of the TE-1. The average settlement rate of TE-4 is 14% greater than that of TE-3.

6. Assessment of lateral displacements

Figures 6a-d show the lateral displacement δx as a function of depth in TE-1 to TE-4 recorded from the start of construction up to approximately 360 days. In TE-1 and TE-2 (without vacuum pressure, Figures 6a and 6b), the lateral movement is toward the outside of the test platform throughout this period. In TE-3 and TE-4 (with vacuum pressure, Figures 6c and 6d), the lateral displacement is toward the outside until vacuum pressure is applied; however, when the vacuum starts, the movement becomes inward and continues until the vacuum is stopped (on days 290 and 301 for TE-3 and TE-4, respectively). Once the vacuum has stopped, due to the pressure transmitted by the surcharge preloading, the lateral movement is again toward the outside of the embankment. In fact, during surcharge preloading, the soil goes from a state of rest to an active state associated with lateral deformation toward the exterior of the treated area [8].

In contrast, the consolidation caused by suction (vacuum pressure) is isotropic, and the corresponding horizontal displacement is compression toward the treated platform, which decreases the lateral displacement toward the outside of the embankment due to surcharge [13]. In addition, Figure 7 shows that the vacuum techniques implemented in the soft clays of the former Texcoco Lake have influence on surface lateral displacement up to approximately 22 to 35 m from the toe of the embankments. Other investigations have recorded alterations of the surrounding soil due to vacuum pressure up to 10 m from the toe of an embankment [7].

7. Degree of consolidation

Based on the settlements measured by the geotechnical instruments installed in the test sections, it is possible to estimate the ultimate primary settlement with the Asaoka's method [1] and consequently determine the degree of consolidation (DOC) [12] achieved with each technique used. Figures 8a and 8b show the plan distribution of the DOC in the embankments with vacuum pressure, TE-3 and TE-4, obtained from the SPs surface measurements at the end of vacuum pressure application. Because TE-1 and TE-2 did not have installed SPs, these embankments are not included in the calculations. Figure 8 shows that the DOC is more uniform in the area of TE-4 than that of TE-3. For TE-3, the vulnerability was observed in the connections as the ground settled, which caused vacuum losses that affected the settlement [9,10]. In both TEs, the values are higher in the center than in the periphery and much smaller in the corners.

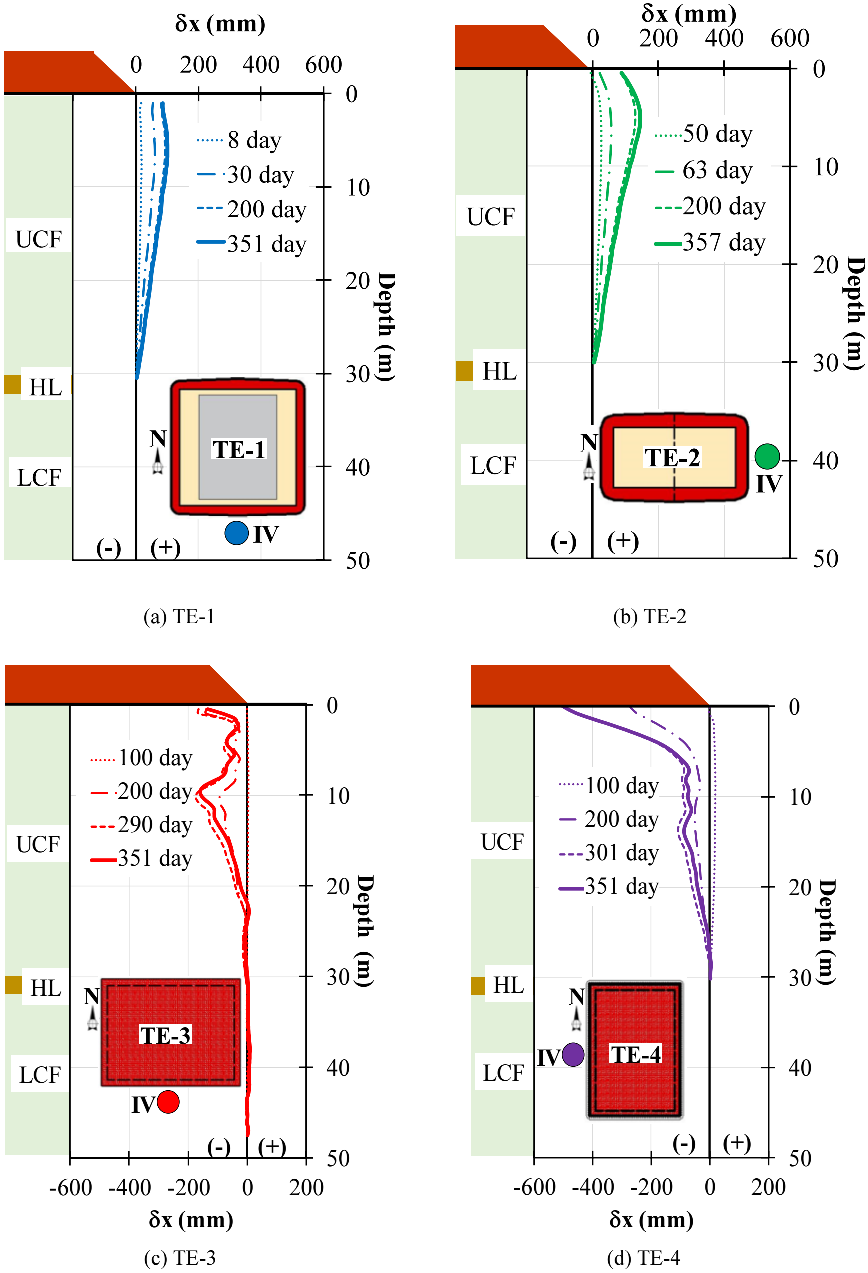

Figure 6. Horizontal displacement δx as a function of depth for TE-1 to TE-4.

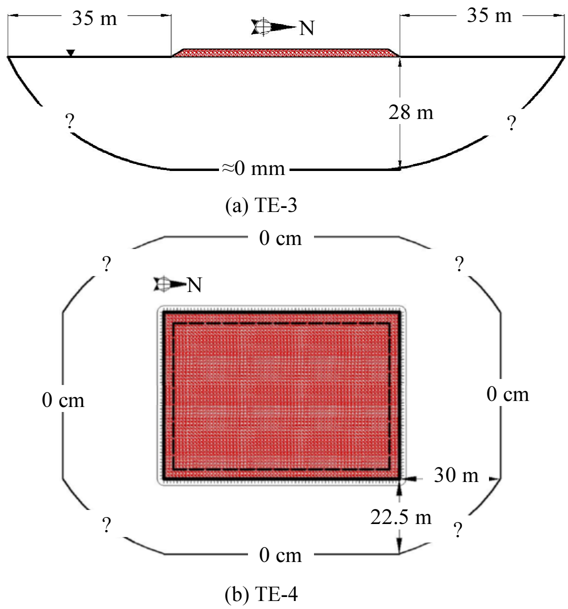

Figure 7. Approximate distance of the effect of vacuum pressure on the lateral displacement measured on the ground surface from the toe of the embankment.

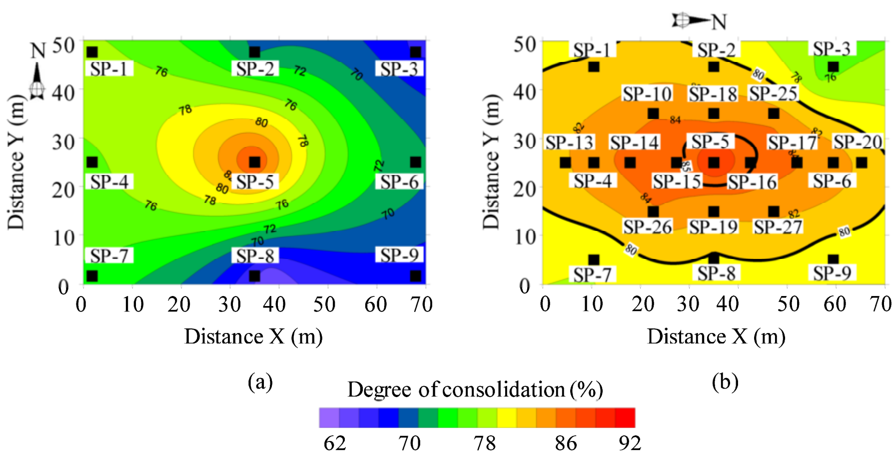

Figure 8. Plan view distribution of the DOC for (a) TE-3 and (b) TE-4 based on surface measurements in SPs.

8. Concluding remarks

The techniques that include PVDs and vacuum pressure significantly accelerate soil consolidation, resulting in higher levels of settlement in less time than other methods of improvement without vacuum pressure. However, applying vacuum pressure is relatively expensive because the vacuum pumps must remain in operation for long periods until the soil is left in a preconsolidated state. For this studied case, the membrane technique resulted more efficient than the drain-to-drain procedure, because larger settlements were reached in the observed period. However, the airtight membrane was vulnerable to the angularity of the *tezontle* used as surcharge preloading; then the placement of a fine sand layer of the same *tezontle*, directly behind the membrane was mandatory. It was also observed that, to maintain the efficiency of the vacuum pressure, the pumps had to remain at the same elevation as the ground in the process of consolidation settlement. In turn, the drain-to-drain vacuum technique was vulnerable in the connections between the horizontal pipes and the PVDs as the ground settled.

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