



AKADÉMIAI KIADÓ

Pollack Periodica •
An International Journal
for Engineering and
Information Sciences

18 (2023) 2, 41–47

DOI:

[10.1556/606.2023.00762](https://doi.org/10.1556/606.2023.00762)

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ORIGINAL RESEARCH
PAPER



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Numerical simulation of replacement method to improve unsaturated expansive soil

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Received: November 25, 2022 • Revised manuscript received: January 24, 2023 • Accepted: February 2, 2023

Published online: April 25, 2023

ABSTRACT

In this paper, a parametric study is done with various removal and replacement materials to study the effectiveness of the removal and replacement method on the wetting depth in the expansive soil and the amount of differential heave caused by climate conditions and common irrigation scenarios for the southern region of Syria. Soil suction changes and associated soil deformations are analyzed using finite element codes, VADOSE/W and SIGMA/W. The paper concludes that the optimum thickness for replacement with high permeability soil should be at least 1 m. In addition, it concludes that replacing soil with a permeability coefficient lower than the permeability coefficient of the site soil contributes to a 56% and 79% reduction in total and differential heave, respectively.

KEYWORDS

expansive soil, unsaturated soil, replacement method, soil suction, soil-water characteristic curve

1. INTRODUCTION

There are numerous ways to reduce the swelling of expansive soils including the removal of a specific surface thickness of the soil and its replacement with improved non-expansive soil [1]. In certain cases, the entire layer may be removed, but on many occasions it proves to be uneconomical. During this process only a specific thickness of expansive soil is replaced and thus it is necessary to determine the minimum thickness that reduces the total and differential heave of the soil while remaining within acceptable limits.

Replacing a specific thickness of expansive soil, the moisture of which changes over time, with non-expansive soil reduces its swelling, so replacing the expansive soil under light structures is an effective and economical method [2]. It is also found that covering the expansive soil with a layer of specific thickness of non-expansive clayey soil greatly reduces its swelling, and reduces differential heave due to its low permeability [3].

Most building codes, for example, the International Building Code (IBC) [4], also recommend this method of improvement when construction work is carried out on expansive soils. The instructions state that the removal of the expansive soil should take place to a depth beyond which the soil moisture is constant. However, Abdelmoneim et al. [3] noted that caution should be exercised or observed when replacing specific thicknesses of expansive soils with non-expansive soils because of their high or low permeability. In addition, due to their contribution to reducing heave to a great extent without problems, the most suitable soils to be applied for replacement are non-expansive soils with low permeability. Replacing a specific thickness of the expansive soil layer with a compacted sand layer will create many problems according to Ahmed [5] because the high permeability of sand will provide conditions conducive to the entry of surface water.

The fluctuation of seasonal humidity in the studied area and the depth of wetting in the soil layer are of particular importance in estimating the value of soil heave, because the expansive soil movement is primarily related to changes in soil moisture content, and the estimation of soil heave is dependent on the aggregation of swelling deformations caused by changes in soil moisture [6, 7]. On the other hand, if there is a mat on the soil, for example, the depth of wetting will remain somewhat isolated and will not be controlled by external climate changes.

The depth of wetting is determined by a large number of different methods. This research is limited to numerical simulations due to the difficulty of other methods and the amount of time they require. In addition to the complexity of this issue in geotechnical engineering [8], and the availability of many commercial software packages suitable for simulation the flow of moisture in the soil, the VADOSE/W program is applied to determine the depth of wetting in the Denver area [9], the HYDRUS program is used to model the movement of soil moisture in the unsaturated zone [10], and the PLAXIS and SEEP/W are used in numerical simulation of soil-atmosphere interaction of a slope in Singapore [11].

This paper addresses a one-of-a-kind investigation into the viability of a replacement method for improving expansive soils with the investigations relying on key unsaturated flow and stress-deformation principles. This work incorporates a parametric study of the thickness and hydraulic conductivity of the replacement to obtain the best material and the optimal thickness of replacement. The expansive soil characteristics and climatic data from the southern region of Syria were applied.

2. RESEARCH MATERIALS AND METHODOLOGY

An analytical method was applied to achieve the objectives of this research. The VADOSE/W finite element program was used in the study of the flow analysis in unsaturated soils, and the SIGMA/W program was used to analyze the deformations under the foundation. The soil suction results obtained from the VADOSE/W were used as inputs to the SIGMA/W since they are ultimately two branches of the same program.

In this paper, the modeling was carried out taking into account that the foundation is an impermeable surface, but flexible enough to be affected by differential heave, and the alternative improved soil is assumed unaffected by moisture.

To achieve the objectives of the research, a model with acceptable dimensions was proposed, which is shown in Fig. 1, and because of symmetry, the study was conducted on half of the model. Several cases were studied in which a partial surface layer of the expansive soil had been replaced by different thicknesses (0.5, 1, 1.5, 2, 4 m). The width of the house applied in the model is 14 m, which is the common dimension of rural houses.

The average annual precipitation in the southern region of Syria over the last thirty years according to meteorological

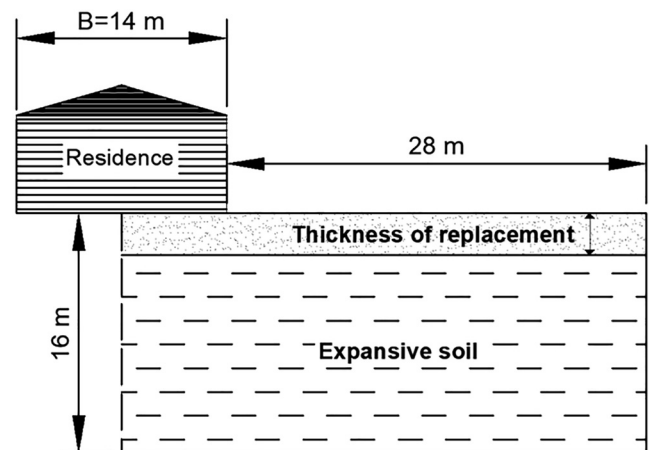


Fig. 1. Dimensions of the cross section used in the analysis (Source: Authors)

information has been about 18.5 cm (Fig. 2) [12]. The analysis in this study was conducted over a year starting from an initial suction of 2000 kPa, given that the ground-water level in the southern region falls within the range of 100–200 m from ground level [13]. An irrigation system is applied at a rate of 130% of the lawn requirements according to Mecham [14], and the water requirement of the lawn is determined using Eq. (1) [15]:

$$ET_c = ETo \times Kc, \quad (1)$$

where ET_c represents the amount of irrigation water to be provided (mm day^{-1}); ETo is the evaporation (mm day^{-1}); and Kc is the crop coefficient depending on the type of crop.

The Soil-Water Characteristic Curves (SWCC) have been determined experimentally based on Al-Majou [16] and converted into the equation of Fredlund and Xing [17] as it is plotted in Fig. 3a.

Table 1 shows the characteristics of the replacement improved soil used in the study, and Table 2 also shows the characteristics of the expansive soil [16]. The initial suction values were taken equal to 65, 200, 140 kPa for the replacement soils with greater, lower, and same permeability to the permeability of the expansive soil respectively, and these values were calculated from the Soil-Water Characteristic Curves (SWCC) of the replacement soils shown in

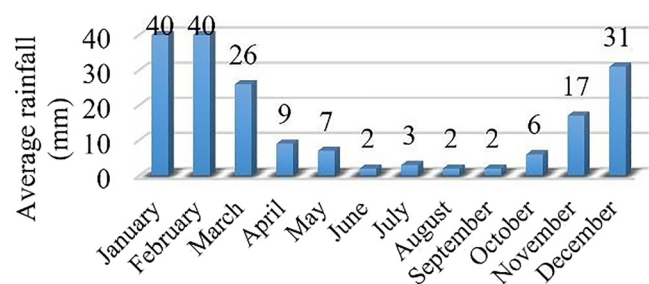


Fig. 2. The average monthly rainfall in the southern region of Syria for the past 30 years, compiled by the Authors based on [12]



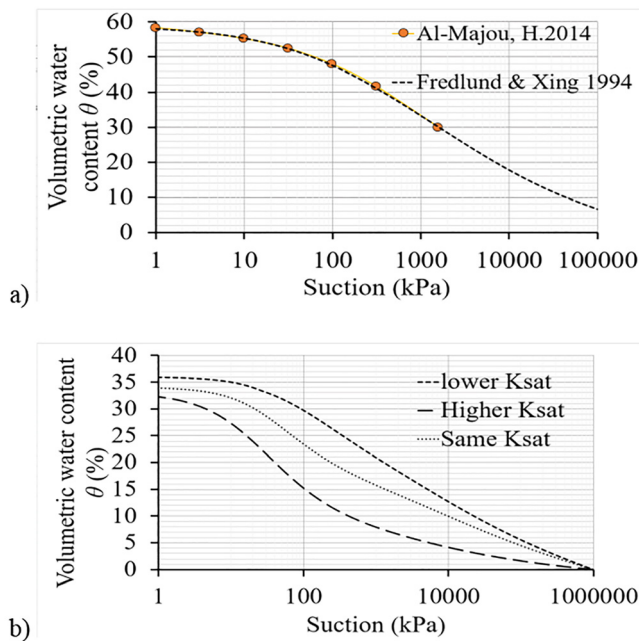


Fig. 3. Soil-water characteristic curve, a) the expansive soil employed in the study, modified after [16], b) replacement, non-expansive improved soil, defined by [17]

Fig. 3b, based on ideal values of the degree of saturation of compacted replacement soils according to [18].

The correct validation of the problem is among the most significant issues to address. To validate a model, the predictions of a numerical approach are compared to the results of engineering programs (Abaqus, Plaxis) that use independent solutions or field measurements [20, 21]. Due to the lack of field measurements in Syria, showing the change of suction vs. depth can be relied upon for validation. Therefore, the authors relied on the field measurements created by Overton et al. [9] to validate the VADOSE/W program, where Fig. 4 shows the suction section in the soil layer for the initial (before construction) and final states (after construction).

The SIGMA/W program was validated according to Eq. (2), which was shown to be able to simulate the heave of expansive soils for many case studies according to Tu [22].

Table 2. Expansive soil characteristics, compiled by the authors based on [17]

	LL (%)	96.90
	PL (%)	41.30
	G (–)	2.69
	γ_d (kN m^{-3})	1.36
Fredlund & Xing parameters	a (–)	140
	m (–)	0.90
	n (–)	0.60
	Saturated volumetric water content (%)	59.10
	K_{sat} (m day^{-1})	$2.10 \cdot 10^{-4}$

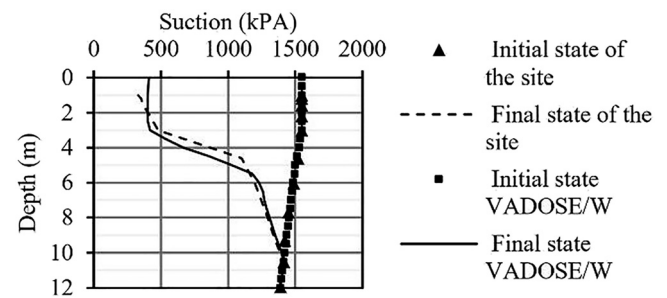


Fig. 4. Results of the VADOSE/W validation, compiled by the authors based on [9]

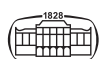
$$\Delta h = C_s \cdot h \cdot \left[\frac{\log(P_0/P_{si})}{1 + e_i} - \frac{\log(P_0/P_{sw})}{1 + e_w} \right], \quad (2)$$

where C_s is the swelling index (–), h is the thickness of soil layer (m), e_i is the initial void ratio (–), e_w is the void ratio after wetting (–), P_{si} is the initial swelling pressure (kPa), P_{sw} is the swelling pressure after wetting (kPa), P_0 is the total vertical stress (kPa).

Soil heave was calculated based on SIGMA/W and the previous equation Eq. (2), where $C_s = 0.128$, $e_i = 0.978$, $e_w = 1.0255$, $P_{si} = 154.8$ kPa, $P_{sw} = 58$ kPa, $P_0 = 20$ kPa, $h = 2.5$ m, for the initial and final states of soil suction shown in Fig. 6 (without replacement) obtained from the VADOSE/W, for the site soil characteristics applied in the

Table 1. Characteristics of replacement improved soils, compiled by the authors based on [19, 20]

Type of replacement soil according to the permeability coefficient	Replacement soil with a greater permeability coefficient	Replacement soil with a lower permeability coefficient	Replacement soil with same permeability coefficient
Dry unit weight γ_d (kN m^{-3})	17.700	17.800	18.000
Bulk unit weight γ_b (kN m^{-3})	20.600	21.000	21.100
Saturated volumetric water content θ_{sat} (%)	33.000	36.000	34.000
Coefficient of saturated permeability K_{sat} (m day^{-1})	0.072	$2.10 \cdot 10^{-5}$	$2.10 \cdot 10^{-4}$
Suction corresponding to Air Entry Value (AEV) (kPa)	15.000	60.000	22.000



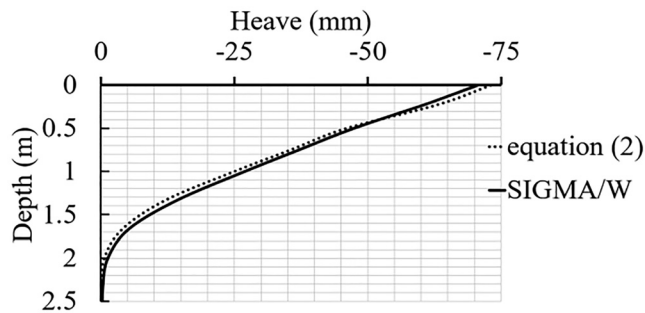


Fig. 5. Results of the SIGMA/W calibration (Source: Authors)

study. Figure 5 demonstrates that the heave computed using Eq. (2) and the heave calculated using SIGMA/W are almost identical, which confirms the eligibility of the SIGMA/W program to simulate the heave of expansive soil.

3. RESULTS AND DISCUSSION

Figure 6 shows the initial and final state of suction (after a year) under the edge of the house for various thicknesses of replacement soil with higher permeability than the expansive soil. Table 3 shows the depths of wetting for various thicknesses of replacement soil based on Fig. 6, which considers that this depth of wetting, starting from the ground level reaches the depth of equilibrium moisture when the line of final state nearly matches the line of initial state.

It is obvious from Table 3 (third column) regarding replacements with high permeability soils, the depth of wetting within the expansive soil increases significantly when replaced by a 0.5 m thick layer, but with the increase in the thickness of the replacement, the depth of wetting starts to decrease. The replaced soil will allow wetting to spread over greater distances under the building and prevent its concentration at the edge of the building only as it is shown in Fig. 7 explaining the return of the wetting depth to a decrease with an increasing thickness of replacement with high permeability soils. The arrows in Fig. 7 represent the flow of moisture, and their size indicates the magnitude of the flow.

Figure 7 shows that if the replacement soil has permeability greater than the permeability of the original expansive soil underneath it, the water collected at the edge of the house will easily enter the replacement soil, causing moisture to spread to greater depths under the mat. As a result there

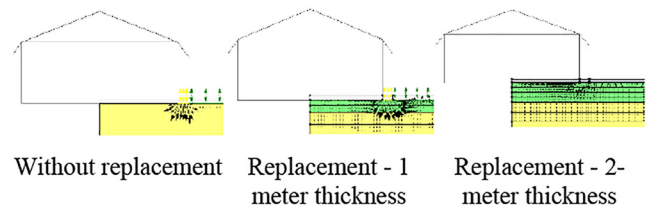


Fig. 7. Easy flow of moisture under mat when replacing it with highly permeable soil (Source: Authors)

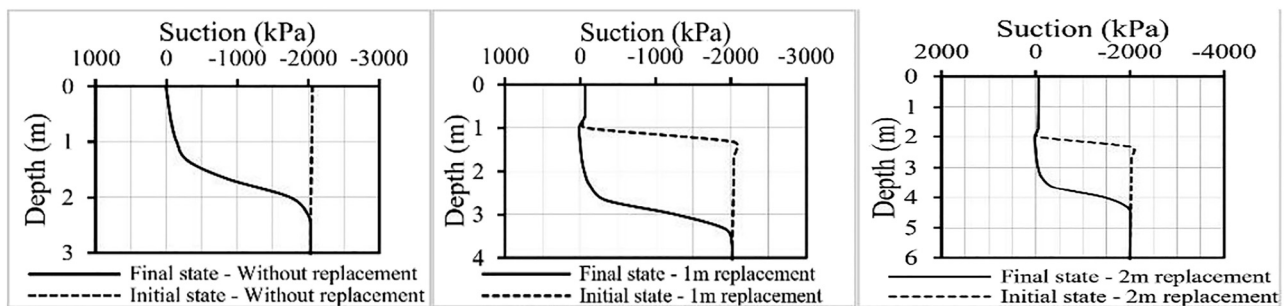


Fig. 6. Initial and final state of the suction sections under the house edge for some thicknesses of replacement soil with greater permeability than the site expansive soil (Source: Authors)

Table 3. Depths of wetting for different thicknesses of replacement soil under the house edge (Source: Authors)

	Thickness of replacement (m)	Depth of wetting, starting from the ground level (m)	Wetting thickness below the replacement soil (m)
Without replacement	0	2.49	2.49
Replacement with greater K_{sat}	0.50	3.40	2.90
	1.00	3.79	2.79
	1.50	4.26	2.76
	2.00	4.74	2.74
	4.00	6.65	2.65
Replacement with same K_{sat}	0.50	2.96	2.46
Replacement with lower K_{sat}	0.50	2.61	2.11

will be no concentration of humidification at the edge of the house only, but under the entire house mat.

Figure 8 shows the results of the deformation calculations using the SIGMA/W for different replacement thicknesses and the values of the heave occurring are shown directly below the house mat.

The curves in Fig. 8 show that replacing a limited partial thickness of the expansive soil with a replacement soil where the permeability is greater than the permeability of the original expansive soil will make the total heave below the edge of the house mat decrease as the replacement thickness of the soil increases, while the values of heave at the center of the house increase with increasing the replacement thickness of the soil. As a result, the differential heave (the difference between the center heave and the edge heave) below the mat at the surface of the ground will decrease with the increase of the replacement thickness of the soil.

When a limited portion of the expansive soil is replaced with a replacement soil which has permeability equal to or less than that of the original expansive soil, the total and differential heave values are reduced because water entry becomes more difficult and the depth of wetting is reduced, resulting in a reduction in the change in suction under the house mat.

Figure 9a shows the change of differential heave over time for different thicknesses of replacement soil with permeability coefficients greater than the permeability coefficient of the original expansive soil. The curves show a decrease in the differential heave after 270 days. Due to the intensity of the precipitation, moisture penetrates to greater depths in the soil at the bottom of the middle of the building, increasing total soil heave in this area, as it is shown in Fig. 9b, and thus decreasing differential heave.

The relationship between differential heave and replacement soil thickness is depicted in Fig. 10a when the permeability of the replacement soil is greater than the permeability of the site expansive soil. According to Fig. 10a, the thickness of the replacement should not be

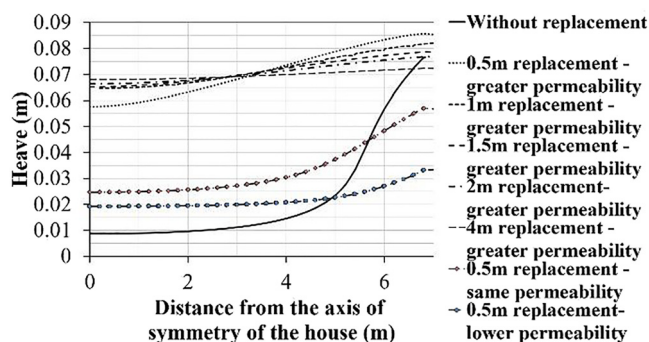


Fig. 8. The distribution of heave values under the house mat for different soils and different values of replacement thicknesses (Source: Authors)

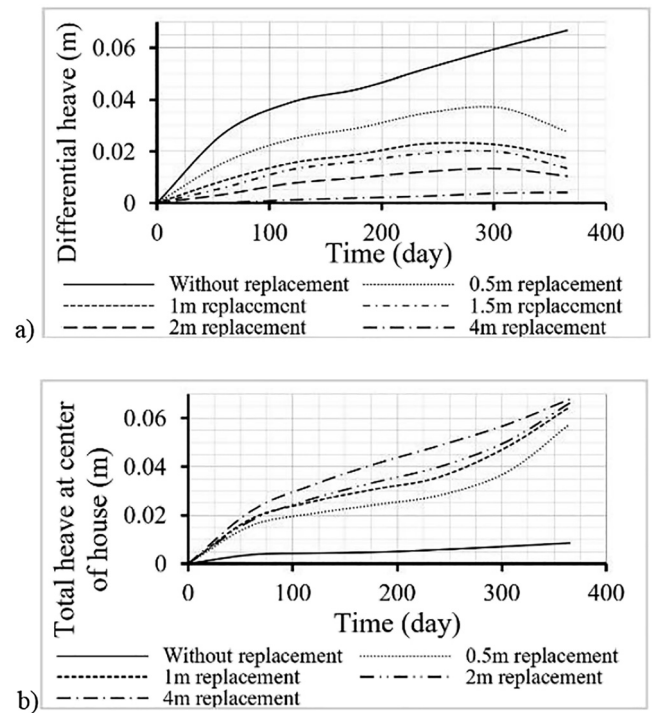


Fig. 9. a) Differential heave vs. time, b) Total heave vs. time at the center of the house, for different replacement thicknesses (replacement soils with greater permeability) (Source: Authors)

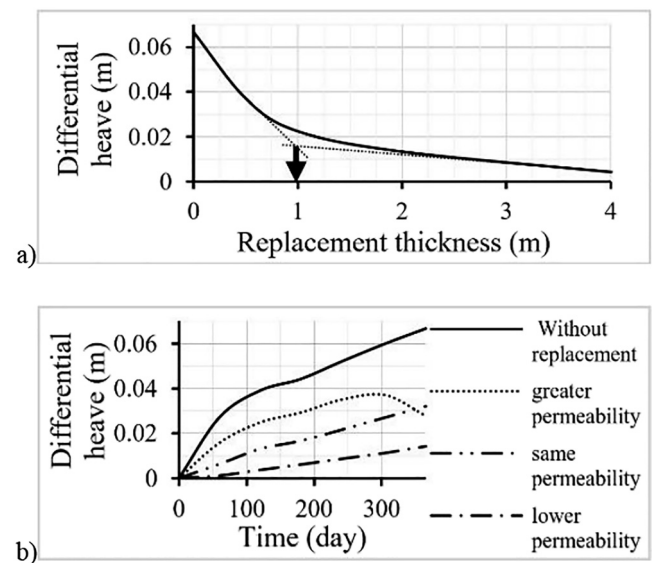


Fig. 10. a) Differential heave relationship with replacement thickness of greater permeability, b) differential heave vs. time for a replacement soil of 0.5 m thickness (Source: Authors)

less than 1 m to ensure as little differential heave as possible. Figure 10b shows a comparison of the different cases of replacement soil with a thickness of 0.5 m where permeability is greater, the same, and less than the permeability of the original expansive soil and Table 4 shows the reduction ratios.

Table 4. Reduction percentages for both total and differential heave for replacement soils (Source: Authors)

	Differential advancement (m)	Total heave (m)	Reduction of differential heave (%)	Reduction of total heave (%)
Without replacement	0.067	0.075	0	0
0.5 m replacement–greater permeability	0.037	0.085	–44.500	13.400
0.5 m replacement–same permeability	0.032	0.057	–51.900	–24.600
0.5 m replacement–lower permeability	0.014	0.033	–78.800	–55.700

Figure 10b and Table 4 demonstrate that replacing soil with a permeability coefficient lower than the permeability coefficient of the site soil produces better results, contributing to a 55.7% and 78.8% reduction in total and differential heave, respectively.

4. CONCLUSION

Based on the theoretical and analytical study of the research, the results can be summarized as follows:

1. Replacing a specific thickness of the expansive soil layer is an effective and useful way to reduce the effects of suction that cause total and differential soil heave;
2. Substituting a specific thickness of the expansive soil layer with a replacement soil with a permeability coefficient of 2.10×10^{-5} , which is ten times lower than the permeability coefficient of the original expansive soil (2.10×10^{-4}), effectively contributes to reducing the depth of wetting and suction changes. In turn the total and differential heave caused by the expansive soil's suction changes are reduced by 55.7% and 78.8%, respectively, as this alternative covering layer slows downward leaching and upward evaporation from and in the expansive soil;
3. Each type of soil has an ideal replacement depth, which is the depth that makes total and differential heave at their minimum value. The value of this ideal depth should not be less than 1.0 m for replacement soils with a coefficient of permeability higher than the coefficient of permeability of the original expansive soil underneath;
4. Replacing a specific thickness of expansive soil with a replacement layer with a high permeability coefficient (such as sand cushion) increases the depth of wetting and thus the activity of the changes in suction.

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