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Research Article

Effect of Sand Compaction Piles on the Swelling and Shrinkage Behavior of Expansive Soil

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This study aims to investigate the effect of sand compaction piles on the swelling and shrinkage behavior of expansive clay soil. A series of experimental laboratory tests were carried out using the modified Proctor mold and a circular footing. The diameter of the sand compaction pile was selected to give a replacement area ratio equal to 57%. To model the swelling and shrinkage cycles, water was added to the sample and the heave was recorded at regular time intervals. The shrinkage was obtained by heating the outer surface of the modified Proctor mold at a temperature of 110°C ± 5°C by a development heating system designed for this purpose to accelerate the shrinkage process. The vertical movement was recorded at regular time intervals. The swelling and shrinkage cycles were carried out under an externally applied pressure equal to 120 kPa. The main results of this study showed that, for untreated expansive soil, the swelling potential reaches the highest value at the second cycle and started to decrease for the subsequent cycles. After the fourth cycle, the swelling potential decreases and reaches about half the value of the initial swelling potential and the equilibrium state occurs. For expansive soil treated with a sand compaction pile, it is found that there is a significant reduction in both swelling and shrinkage potential. Moreover, it is observed that after the first cycle both the swelling and shrinkage potential decrease significantly, and both reach a negligible value after the second cycle.

1. Introduction

Expansive clay soils have the tendency to have a change in volume in response to a change in moisture content. These soils swell and shrink when the moisture content increases and decreases, respectively. This phenomenon of cyclic swell-shrink of expansive soil generates considerable damage to structures built on, in, or with such soils, particularly in low-rise buildings, roads, and buried utilities [1–4]. Within the last decades, researchers made great efforts to find different methods to overcome or reduce the swelling potential of expansive clay soils. These methods can be divided into two main methods, the first one is the modified properties of the expansive clay soils, and the other is the adopted special foundation techniques. Certain additives such as lime, fly ash, cement, cement kiln dust, quarry dust, polymers, and chemicals are used to modify the properties of expansive clay soils. Moreover, replacement of expansive soil by nonexpansive soil, artificial clay sand, and clay gravel mixes was used widely [5–8]. Furthermore, some special foundation techniques such as belled piers, underreamed piles, helical piers, micropiles, granular piles (GP), granular anchor piles (GPA), sand compaction piles (SCP), and lime columns have also been suggested as an advanced foundation technique in expansive soils [9–15]. Usually, determining the swelling potential of expansive clay soils is performed by one cycle of wetting, although seasonal fluctuation leads to notable changes in the moisture content of expansive clay soils, which, in turn, exposes it to cyclic swelling and shrinkage. The swell-shrink behavior of soil is a complicated phenomenon that is not yet well understood, although it has great significance in engineering and environmental practice. Shrinkage in plastic soils generates interparticle tensile stresses, and it is extensively believed that when these stresses exceed the tensile strength, cracks can grow [15]. Several previous investigations revealed that the hydraulic conductivity of cracked soils is several orders of magnitude greater than that of intact soils [16, 17]. Hence, the complete cycle of swelling and shrinking effect on the treated and untreated expansive soil needs to be investigated widely.

Numerous previous studies have been carried out to understand the cyclic behavior of the natural expansive soil. These studies suggested two methods for determining the cyclic swell-shrink behavior of expansive soils, full swell-full shrink, and full swell-partial shrink. In full swell-full shrink, samples are allowed to swell until the major swell is completed or no more swell is observed and dried fully or until the water content draws closer below the shrinkage limit. In full swell-partial shrink, samples are allowed to swell until the major swell is finished or no more swell is observed and dried to their initial water content. Most results of these studies indicated that, for full swelling-full shrinkage cycles, there is an increase in swelling potential for expansive soil. On the other hand, for full swelling-partial shrinkage, the swelling potential decreases. These studies indicated that the reason for this is due to the fact that after the first full shrink cycle, the water content reaches the minimum value, and macrocracks are developed which allow more water content to penetrate the soil pores at the second swell cycle. Moreover, the swelling potential decreases for full swelling-partial shrinkage are due to the fact that after the first partial shrink cycle, the high-water content is existing before starting the second swelling cycle [18–25].

The effect of cyclic swell-shrink on the behavior of natural expansive clay soils is well investigated. However, the effect of this phenomenon on the behavior of stabilized expansive clay soils has not been given good attention. Most of these studies were carried out on chemically stabilized expansive soil to estimate the long-term behavior of structures founded on, in, or by it [26–33]. However, there is another advanced foundation technique using flexible or rigid piles embedded in expansive soils, but the studies carried out in this direction are very few. Some of these studies were carried out using flexible piles (granular pile and granular pile anchor) as reinforced for expansive clay soil [34–36], and others were carried out on rigid piles (belled piers, underreamed piles, helical piers, and micropiles) as reinforced for expansive clay soil [37]. Most of these studies focused their attention on determining pull-out forces in which these piles can withstand. Very few of them were interested in studying the vertical movements of expansive soil treated with these piles during swelling and shrinkage cycles.

Some researchers have found that the assembly of granular piles or granular columns, which includes stone columns, rammed aggregate columns, and sand compaction columns, is the best effective and efficient method to improve the load-carrying capacity and minimize the settlement of soft clay, loose sand, and expansive soil. These columns have higher strength and stiffness than the surrounding soil. Those researchers carried out laboratory tests on granular piles created in the expansive soil. End bearing granular piles were created in the expansive soil and the load tests were done. The results indicated that the load-carrying capacity of a footing founded on a granular pile is more than the consistent value for the footing founded directly on the soft expansive soil bed. It is concluded that the loss in strength and extreme settlement of the expansive soil, which is due to soaking with water, can be greatly reduced by using granular piles in expansive soil [38–40].

Sand is often readily available near most of the construction sites in Egypt and it is considerably less expensive than other handled materials such as crushed stone. However, either bottom feed stone column equipment or sand compaction pile equipment can be used to construct sand piles. Additionally, the hydraulic conductivity of compacted sand is less than other granular materials (gravel or crushed stone). For these reasons, the use of sand compaction piles in expansive soil is very suitable in Egypt. This study is considered an extension of the previous study conducted by [13]. The main result of that previous study revealed that using sand compaction piles as a deep replacement technique, with a replacement area ratio (RAR = 57%) for the treatment of expansive soil, was efficacious in arresting the heave of expansive soil substantially. The efficacy of sand compaction pile with RAR = 57% during wetting and drying cycles should be established before it can be recommended for application in the field. Thus, this study is an attempt in that direction.

2. Experimental Program

Two tests were carried out to investigate the effect of repeated cycles of wetting and drying on the behavior of untreated expansive clay soils (UECS) and treated expansive clay soils with sand compaction piles (TECS).

3. Material Properties

The basic materials used in this study are expansive clay soil representing the soil to be improved and graded sand as a sand compaction pile. The properties of these materials are as follows.

3.1. Clay. The expansive clay soil used in this study was collected from a depth of 2.0 m below the ground surface in Ahkmim new city, Sohag, Egypt. The main properties of used expansive clay soil are presented in Table 1.

The high liquid limit and high plasticity index indicate the potential for significant volume change of that soil. Besides, a free swell index of 177% shows that the soil has a high degree of expansiveness.

3.2. Sand. The properties of used sand as forming sand compaction pile (SCP) are listed in Table 2. The particle size distribution curve for used sand is shown in Figure 1.

3.3. Water. Tap water was used in the preparation of expansive clay samples as well as in the soaking process.

4. Test Setup and Procedure

4.1. Untreated Expansive Clay Soil. Untreated expansive clay soil model was prepared first to take its results as a reference

Table 1: Properties of used expansive clay soil.

Properties	Values
Specific gravity	2.66
Sand	2%
Silt	22%
Clay	76%
Liquid limit (%)	85
Plastic limit (%)	32.4
Plasticity index (%)	52.6
Free swell index (%)	177
Natural dry density (kN//m^3)	20.21
Natural moisture content (%)	8.69
USCS and IS classification	CH

Table 2: Properties of used sand.

Properties	Values
Specific gravity	2.76
Maximum dry density (kN//m^3)	20.5
Optimum moisture content (%)	6.4
USCS and IS classification	SP

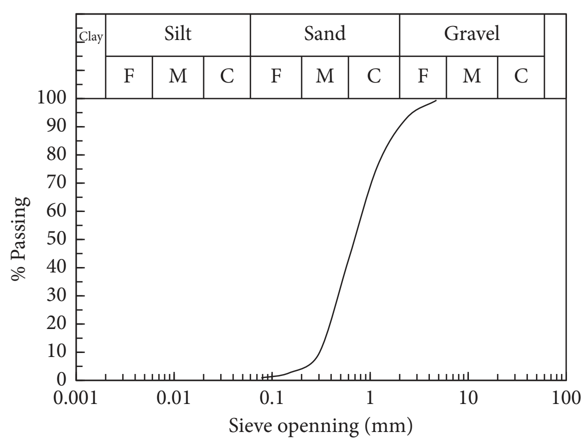

Figure 1: Particle size distribution curve for used sand.

for comparison with the expansive soil treated with SCP. To prepare the expansive clay soil model with a natural dry density (20.21 kN/m^3) and natural moisture content (8.69%), the expansive clay soil sample with a weight of 7 kg was crushed using a rubber hammer and sieved through sieve No. 8 (2.36 mm). The passing soil was dried in the oven at 105°c for 24 hours. The required amount of dry expansive soil to fill the modified Proctor mold (MPM) until 150 mm height with the target density (20.21 kN/m^3) was weighted (the dimensions of MPM are 152 mm internal diameter and 168 mm height). The dry expansive soil was then mixed thoroughly with a predetermined amount of water to achieve the required natural moisture content (8.69%). The mixture (soil/water) was kept in an airtight container for 24 hours to allow for uniform distribution of water.

The internal wall surfaces of the mold were greased with a lubricant material to minimize the sidewall friction resulting from soil expansion upon clay wetting. The soil-water mixture was compacted in three equal layers, each with a thickness of 50 mm. Each layer was statically compacted until the required height. Static compaction by hydraulic jack was used because it gives the greatest uniform and repeatable results. Five holes, each with a diameter of 4 mm and a depth of 150 mm, were created in the soil model and filled with sand to accelerate the water leakage and the swelling process. One hole was made in the middle of the sample model, and the other four were uniformly distributed around the soil sample center, so the radial distance was equal to a quarter of the sample diameter.

The filter paper was placed over the top surface of the soil model. A rigid circular steel plate with a 150 mm diameter and 10 mm thickness was used as a footing and placed over the filter paper. The footing had many holes with a 3 mm diameter to allow water to enter the soil model. Then, the prepared mold was placed under the system of loading as shown in Figure 2. The system of loading is consisted mainly of precast circular plain concrete blocks to give a surcharge pressure equal to 120 kPa. This pressure is equivalent to the pressure that the foundations of residential buildings are often designed on it and is suitable for such types of clay soil when exposed to wetness.

Two dial gauges with a sensitivity of 0.01 mm and a travel of 25 mm were fixed on the top of the system of loading to measure the vertical movement of the soil specimen during the swelling and shrinkage process, as shown in Figure 2. Water was added to the system, and the level of water over the footing was kept constant during the test period. The vertical displacement was monitored continuously by taking the two dial gauge readings at regular interval times until the dial gauge readings had no change for at least two consecutive days.

4.2. Expansive Clay Soil Treated with SCP. Modified Proctor mold was also used in the experimental test. SCP with a diameter of 114.7 mm and a height of 150 mm was prepared. PVC pipe with an outer diameter of 114.7 mm was used to create SCP in the center of MPM. A circular hollow wooden plate (CHWP) with an internal diameter of 116.7 cm, an outer diameter of 150 mm, and thickness of 30 mm was used temporarily as a centralizer to keep SCP centered. The outer surface of the PVC pipe was greased with a lubricant material to facilitate the process of pulling. The amount of dry expansive soil required for filling the space between the PVC pipe and the mold to give the required natural dry density (20.21 kN/m^3) was determined from the same used soil. The amount of water to give the natural moisture content (8.69%) was determined.

Water and dry soil were mixed carefully to have a homogenous mixture. The amount of dry sand and the corresponding amount of water required to fill the hollow created by PVC pipe with the specified maximum dry density (20.5 kN/m^3) and optimum moisture content (6.4%) were determined and mixed carefully. Each type of mixture (dry expansive soil/water and dry sand/water) was kept in airtight containers for 24 hours to allow uniform distribution of moisture. Each of them was divided into three equal amounts, where each amount gave 50 mm height in the MPM.

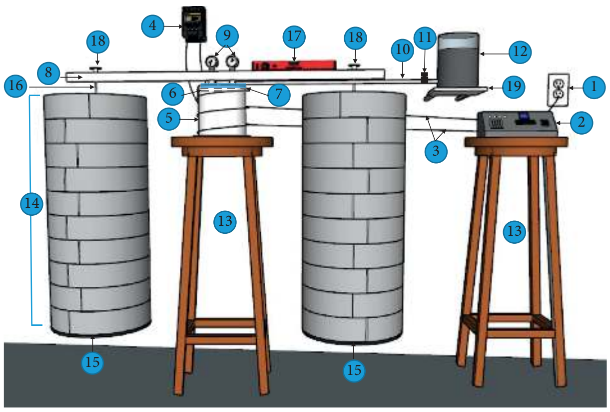

Figure 2: Schematic diagram of the laboratory experiments setup.

After cleaning the MPM from any dust, the PVC pipe was placed in its center and adjusted in the center by using CHWP. The first amount of expansive soil/water mixture was placed around the PVC pipe and the top surface was leveled. Then, the first clay layer was compacted by knocking on the CHWP using a steel rod with $\varnothing = 20mm$ until reaching a height equal to about 55 mm from the mold base. Next, the PVC pipe was withdrawn completely, leaving a hole behind. The first amount of dry sand/water mixture was placed carefully in the hole and compacted slowly by the steel rod until reaching the same level of the around expansive soil.

After that, the mold was placed under the hydraulic jack to compact the sand pile and the surrounding expansive soil until both reached the required level of 50 mm from the mold base. The same procedure was repeated for the second and third layers for expansive soil and sand piles. After the compaction had been completed, the final surface of the expansive soil/SCP model was leveled off and the filter paper was placed. The used footing was placed on the filter paper. The preparing mold was placed under the loading system as shown in Figure 2 and the same procedure for adding water and recording the two dial gauge readings was followed as explained in the previous section. The detailed components of the expansive clay soil/SCP model are shown in Figure 3.

5. Mechanism of Swelling and Shrinkage Process

5.1. Swelling Process. After preparing and placing the expansive clay soil model for both cases treated and untreated under the system of loading, which is shown in Figure 2. The two dial gauge readings were adjusted to zero, and water was added continuously from the top until the expansive clay beds were completely inundated. Proper precautions were taken to have a constant water level above the soil specimen during the swelling process, where the water reservoir was fixed at a level such that the level of water in both the water reservoir and above the soil specimen was constant during the test time, and the valve was set to control the passage of water that is proportional to the water flow in the soil as shown in Figure 2. The vertical displacement was monitored continuously by taking the two dial gauge readings at regular time intervals till the dial gauge readings had no change for at least two consecutive days.

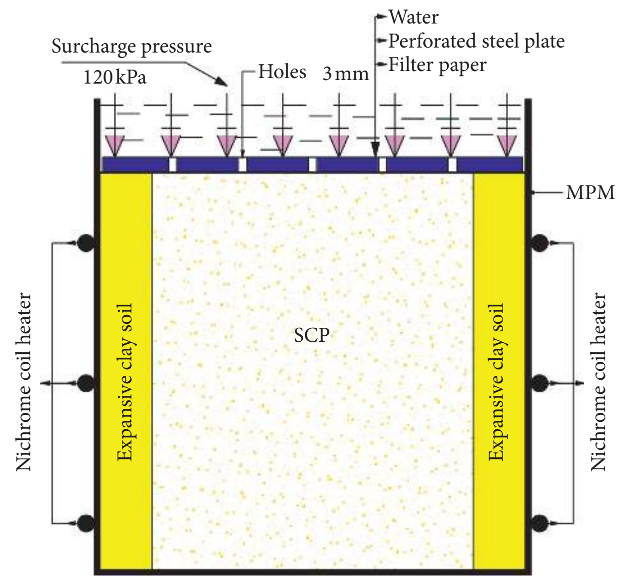

Figure 3: A vertical section of the laboratory model.

5.2. Shrinkage Process. A heating system was developed for the shrinkage process. It consists of a nichrome coil heater wrapped around the modified Proctor cylinder with three rolls with equal spacing. The two ends of the nichrome coil heater were connected to porcelain connectors to which power supply was provided through a temperature controller. Moreover, the two ends of the nichrome coil heater were connected to a temperature indicator as shown in Figure 2. After swelling reaches the equilibrium state, the shrinkage process started. The tap water above the soil specimen was removed by using a medical syringe; after that, the power supply was switched on and the temperature controller was adjusted at (110 ± 5) to maintain a constant temperature throughout the shrinkage process. The vertical movement of the expansive clay soil specimen during the shrinking process was recorded as the swelling process. By the end of the swelling and shrinkage process, the first cycle was completed. For subsequent cycles, the same sequences were followed.

6. Results and Discussion

6.1. Deformation During Wetting and Drying Cycles for UECS. The vertical displacement ratio of the untreated expansive clay sample is presented as the change in height (ΔH) of the sample during either swelling (wetting) or shrinkage (drying). It is expressed as a percentage of the initial height of the sample at the beginning of the first swell-shrink cycle (H). By plotting the vertical displacement ratio of the untreated expansive clay sample for several swell-shrink cycles, the percentage change in the height of the clay sample during any of the swelling or shrinkage cycles can be observed as shown in Figure 4. From this figure, it can be observed that

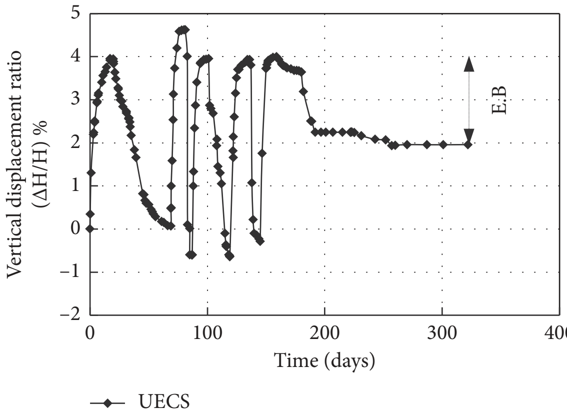

Figure 4: Vertical displacement ratio versus time during wetting and drying cycles.

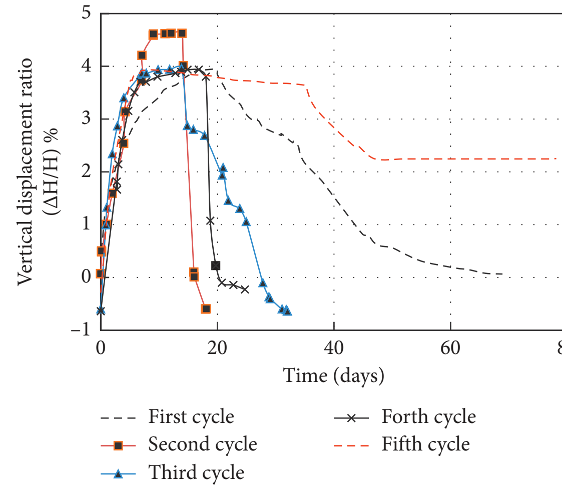

Figure 5: Vertical displacement ratio versus time for each cycle for UECS.

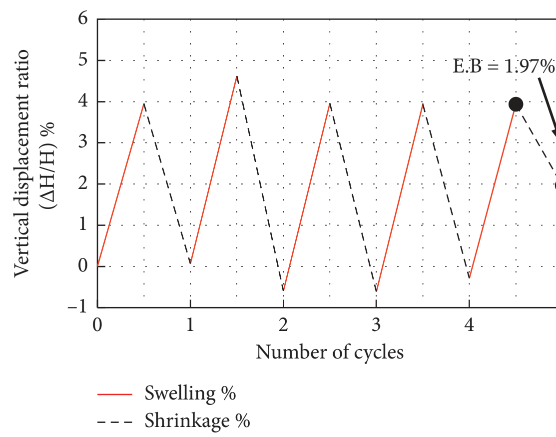

Figure 6: Vertical displacement ratio versus the number of cycles for UECS.

the maximum swelling and shrinkage potential occurred at the second cycle. However, in the subsequent cycles, there is a slight decrease in the values of both swelling and shrinkage potential and the equilibrium state occurred at the fifth cycle due to the fatigue of soil. The equilibrium bandwidth (EB) reaches the lowest value. The bandwidth of vertical movement at equilibrium state between equilibrium swollen level and equilibrium shrunken level is termed as equilibrium bandwidth (EB) [25]. This result is in good agreement with the results obtained by [20, 25].

In addition, the water content of the expansive clay soil was determined at the end of the experiment. It was determined at three positions: at the top surface of the soil model, at the middle, and at the bottom, and its values were found equal to 1.786%, 1.523%, and 1.966%, respectively. The values of water content ensure that the temperature was distributed uniformly around the soil model. Furthermore, this indicated that the developed heating system worked very efficiently.

On the other hand, the average water content is less than the natural water content of expansive clay soil, which ensures that the shrinkage pattern used in the experiment is a full shrinkage pattern. The results of swell-shrink behavior for each cycle can also be plotted as shown in Figure 5. This figure clearly shows that, for each cycle, there is a constant value after reaching the maximum value for swelling or a minimum value for shrinkage before starting the next cycle. Moreover, this figure clarifies that the maximum swelling and shrinkage occurred in the second cycle and the minimum swelling and shrinkage occurred in the fifth cycle.

The results of swell-shrink experiments can also be drawn as shown in Figure 6, where the maximum vertical displacement ratios at the end of each swelling and shrinkage cycle were plotted. It can be clearly seen from this figure that the vertical displacement ratios under surcharge pressure of 120 kPa in the first cycle are 3.95% and 3.88% during wetting and drying, respectively. This means that the amount of shrinkage during drying is less than the amount of swelling during wetting. In the second cycle, the vertical displacement ratios are 4.55% and 5.21% during wetting and drying, respectively. This means that the amount of shrinkage during drying is greater than the amount of swelling during wetting. In the third cycle, the vertical displacement ratios are 4.55% and 4.57% during wetting and drying, respectively. This means that the amount of shrinkage during drying is equal to the amount of swelling during wetting. In the fourth cycle, the vertical displacement ratios are 4.54% and 4.22% during wetting and drying, respectively. This indicates that the amount of shrinkage during drying is less than the amount of swelling during wetting. In the fifth cycle, where the soil sample reaches the equilibrium state, the vertical displacement ratios are 4.22% and 1.96% during wetting and drying, respectively. This clarifies that the amount of shrinkage during drying is much less than the amount of swelling during wetting.

This behavior is illustrated graphically in Figure 7. From this figure, it can be generally said that by increasing the number of wetting and drying cycles under a surcharge pressure of 120 kPa, except for the second cycle, the potential of swelling and shrinkage decreases, but the rate of shrinkage decrease is greater after the third cycle. This behavior was explained by [38] where the original structure of the

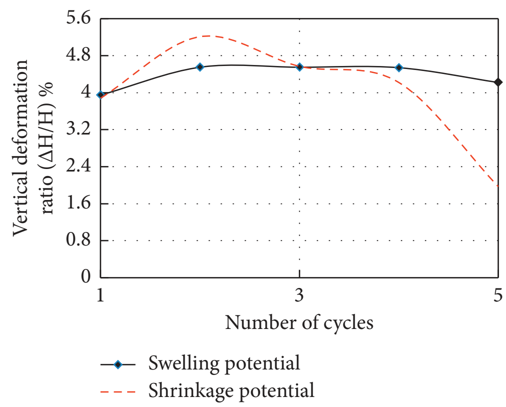

Figure 7: Swelling/Shrinkage potential versus the number of cycles for UECS.

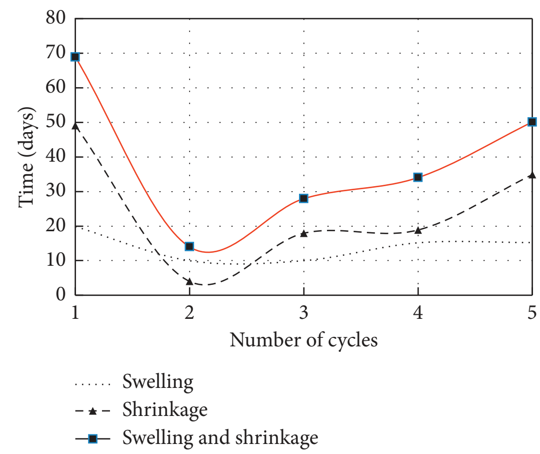

Figure 8: Time required for each stage of the cycle for UECS.

expansive clay soil is changed after the first cycle and, by repeating the cycles of wetting and drying, causes the aggregation and rearrangement of the structure of the soil mass.

6.2. Effect of Number of Cycles on the Duration Time for Each Cycle for UECS. The relationship between the number of cycles and the duration time for each cycle is shown in Figure 8. The duration time for each stage of the cycle (swelling or shrinkage) was calculated as the time from starting swelling or shrinkage until reaching a constant value without counting the time during the equilibrium state. From this figure, it was found that the duration time required for the first cycle (swelling/shrinkage) is the maximum and decreases to the minimum value at the second cycle; after that, the duration time for both swelling and shrinkage increases. This behavior can be attributed to the fact that at the first cycle the seepage of water through the clay sample or the hydraulic conductivity of the soil sample is very small because there are no cracks in the clay sample, and it has the maximum density. After shrinkage in the first cycle, a reduction in soil sample diameter is accompanied by both the development of shrinkage cracks and the creation of a gap between the soil sample and the mold cylinder wall. These cracks and gaps helped the infiltration of water in the soil sample; in other words, the hydraulic conductivity increased at the second swelling cycles [17]. Therefore, when adding water to the clay sample in the second cycle, the infiltration of water through the clay sample is more, so that the time for second wetting and drying is less than other cycles and the water content is more which helps in increasing the swelling in the second cycle and the evaporation of water from the pores is faster.

After that, these cracks and gaps are decreased with an increasing number of cycles due to a self-healing process which negatively affects the hydraulic conductivity [17]. Thus, the required time for the complete cycle is increased and the swelling value is decreased and reached the equilibrium state after the fifth cycle. This observation is consistent with the results obtained by [19].

6.3. Effect of SCP on the Behavior of Expansive Clay Soil during Wetting and Drying Cycles. The behavior of expansive clay soil treated with SCP is illustrated in Figure 9. It can be observed that the maximum swelling and shrinkage potential occur in the first cycle and both decrease with increasing the number of cycles and the equilibrium state was reached after the third cycle. Furthermore, the irreversible deformation reached 0.096% in the third cycle of wetting and drying. The results of swell-shrink behavior for each cycle can also be plotted as shown in Figure 10. This figure clarifies that, for each cycle, there is a constant value after reaching the maximum value for swelling or a minimum value for shrinkage before starting the next cycle.

Moreover, this figure shows that the maximum swelling and shrinkage occur in the first cycle and the minimum swelling and shrinkage occur in the third cycle. Additionally, the water content of the expansive clay soil and sand compaction pile was determined at the end of the experiment. It was determined at three positions, at the top surface of the soil model, at the middle, and at the bottom of both clay soil and sand pile. The values of water content in clay soil were 2.898%, 3.1%, and 2.721%, respectively, and for sand, they were 0.418%, 0.29%, and 0.4875%, respectively. The values of water content for both clay soil and sand pile ensure that the temperature was distributed uniformly around the soil model. Moreover, this proves that the developed heating system is working very efficiently.

On the other hand, where the average water content is less than the natural water content for both clay soil and sand pile, this ensures that the shrinkage pattern used in the experiment is a full shrinkage pattern.

The results of swell-shrink experiments can also be drawn as shown in Figure 11, where the maximum vertical displacement ratios at the end of each swelling and shrinkage cycle are plotted. It can be clearly seen from this figure that the vertical displacement ratios under the surcharge pressure of 120 kPa in the first cycle are 1.2466% and 1.0566% during wetting and drying, respectively. This clarifies that the amount of shrinkage during drying is less than the amount of swelling during wetting and indicates that the plastic (irreversible) deformation is 0.19%.

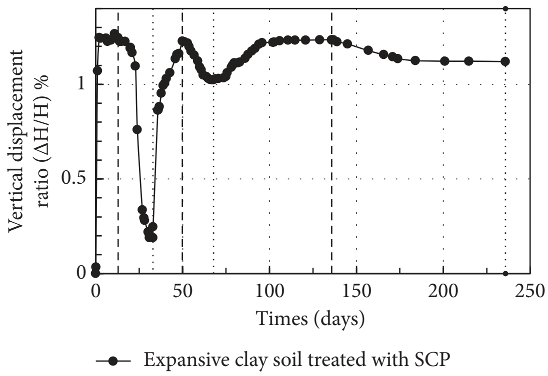

FIGURE 9: Vertical displacement ratio versus time for TECS.

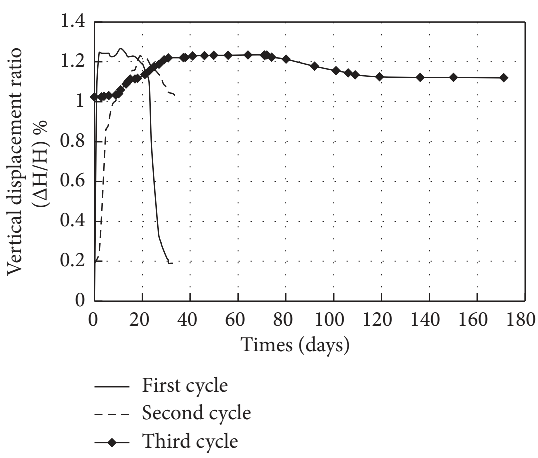

FIGURE 10: Vertical displacement ratio versus time for each cycle for TECS.

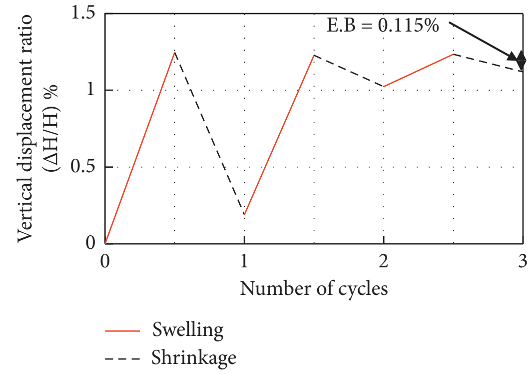

FIGURE 11: Vertical displacement ratio versus the number of cycles for TECS with SCP.

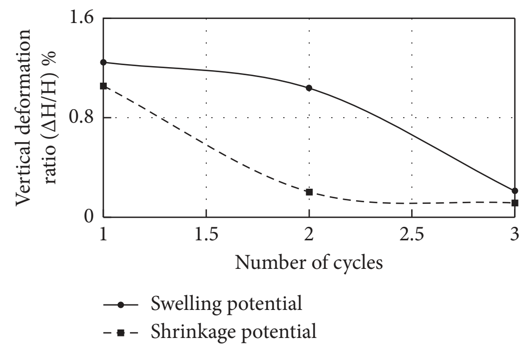

FIGURE 12: Swelling/Shrinkage potential versus the number of cycles for TECS.

In the second cycle, the vertical displacement ratios are 1.0382% and 0.2042% during wetting and drying, respectively. Accordingly, the amount of shrinkage during drying is less than the amount of swelling during wetting and indicates that the irreversible deformation is 0.834%. The irreversible deformation decreases in the following wetting and drying cycles, and after the third cycle, the equilibrium condition is reached with 0.096% reversible deformation, where the vertical displacement ratios are 0.211% and 0.115% during wetting and drying, respectively. Thus, the amount of shrinkage during drying is less than the amount of swelling during wetting.

This behavior is illustrated graphically in Figure 12 where it can be generally said that by increasing the number of wetting and drying cycles under a surcharge pressure of 120 kPa, both swelling, and shrinkage decrease and reach a very small value that can be neglected at the third cycle.

6.4. Effect of Number of Cycles on the Duration Time for Each Cycle for TECS. The relationship between the number of cycles and the duration time for each cycle is shown in Figure 13. From this figure, it can be seen that the duration time required for the first cycle (swelling and shrinkage) is the least, and this duration time increases significantly with the increase of the number of cycles. This behavior can be attributed to the fact that at the first cycle the seepage of water through SCP which has a high hydraulic conductivity is fast. Due to wetting and drying in the first cycle, the microparticles of the clay soil move toward the pores of SCP, which helps in clogging these pores. This leads to a reduction in the hydraulic conductivity of SCP, so the duration time for the subsequent cycles increases.

6.5. Effect of SCP on the Swelling and Shrinkage Potential. To illustrate the effect of using sand compaction piles on both swelling and shrinkage behavior of expansive clay soil, the relationship between the number of cycles and swelling/shrinkage potential for both treated and untreated expansive clay soils is plotted as shown in Figure 14. From this figure, it can be generally noticed that both the swelling and shrinkage potential decrease with increasing the number of cycles for both UECS and TECS. Furthermore, the bandwidths are gradually reduced to insignificant levels.

Moreover, expansive clay soil treated with SCP was taken three cycles to attain a negligible bandwidth compared with untreated expansive clay soil, which has taken five cycles to attain a small bandwidth. This effect can be illustrated in another way by using the reduction factor (RF) for both the swelling potential and shrinkage potential, where

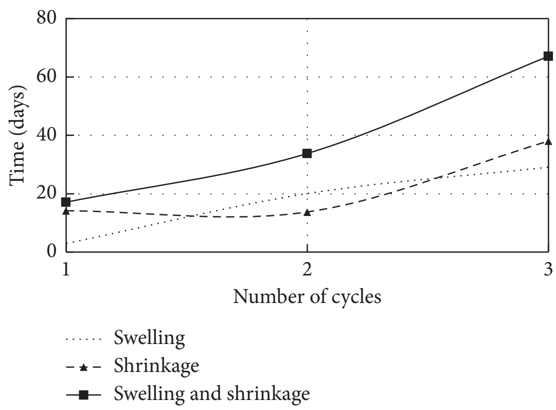

Figure 13: Time required for each stage of the cycle for TECS.

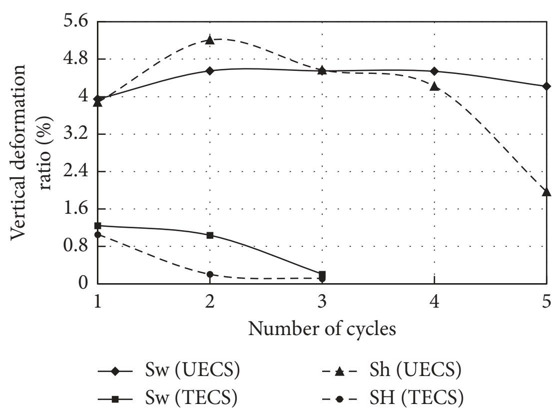

Figure 14: Swelling/Shrinkage potential versus the number of cycles for UECS and TECS.

$$\mathrm{RF\,(Sw)} = \frac{\mathrm{Sw}\,(U) - \mathrm{Sw}\,(T)}{\mathrm{Sw}\,(U)} \times 100,$$
$$\mathrm{RF\,(Sh)} = \frac{\mathrm{Sh}\,(U) - \mathrm{Sh}\,(T)}{\mathrm{Sh}\,(U)} \times 100, \quad (1)$$

where RF (Sw) is the reduction factor of swelling potential, RF (Sh) is the reduction factor in shrinkage potential, Sw (U) and Sw (T) are the swelling potentials for UECS and TECS, respectively, and Sh (U) and Sh (T) are the shrinkage potential for UECS and TECS, respectively.

The relationship between the number of cycles and the reduction factor (RF) for both swelling and shrinkage potential of untreated and treated expansive clay soil is shown in Figure 15. From this figure, it is clear that there is a significant reduction in both swelling and shrinkage potential when reinforced expansive clay soil was treated with SCP, where it reaches 68.41% and 72.77 in the first cycle, 77.18% and 96.08% in the second cycle, and 95.36% and 97.48% in the third cycle, respectively. Moreover, it can be observed that RF increases as the number of cycles increases for both swelling and shrinkage potential and reaches the maximum at the second cycle for shrinkage and at the third cycle for swelling.

The decrease in the swelling potential is ascribed to a gradual demolition of the matrix of the clay structure due to the cyclic swelling-shrinkage process. Also, the cyclic

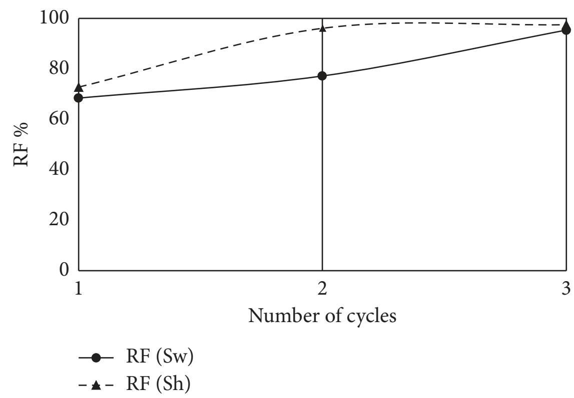

Figure 15: Reduction factor versus the number of cycles for UECS and TECS.

swelling-shrinkage process causes reconstruction and reorientation of the structure of the large microaggregates by the disorientation of structural elements. As a result, all these phenomena change the expansive behavior of natural clayey soil samples with an increasing number of swelling-shrinking cycles due to the wetting-drying cycles [18].

7. Conclusion

Based on the experimental results and analysis obtained from this study, the following important conclusions can be drawn:

(1) The maximum swelling occurs in the second cycle for UECS and decreases gradually in the subsequent cycles and reaches an equilibrium state after the fifth cycle

(2) The use of sand compaction pile (SCP) with RAR 57% in the reinforcement of expansive clay soil shows a considerable decrease in swelling and shrinkage potential and reaches an equilibrium state after the third cycle, under a surcharge pressure equal to 120 kPa

(3) The potential of swelling and shrinkage decreases with increasing the number of wetting/drying cycles for both UECS and TECS

(4) For treated and untreated expansive clay soils, it is essential to determine the swelling value from the first cycle for the short term to imitate the field condition after compaction. It is also vital to study the climate cycles to imitate the field condition for the long term

(5) Swelling and shrinkage potential of expansive clay soil can be reduced significantly by using SCP with a replacement area ratio equal to 57%, under surcharge pressure equal to 120 kPa. This deep replacement technique can be used instead of the shallow replacement technique which is known as a sand cushion

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The author declares that he has no conflicts of interest.

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