Indian Geotechnical Journal, 39(4), October 2009, 387-398

Stress History of Desiccated Expansive Soil

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Introduction

Soils that have potential for shrinkage or swelling under changing moisture conditions are called expansive soils. Clay mineralogy, soil-water chemistry, plasticity, soil structure, dry density and initial moisture content are the important causes for the cyclic swell-shrink movement of expansive soils. Most countries in the world such as Australia, China, India, South Africa, North America, etc., have problems with expansive soils. Expansive soils cover about 2 percent of Earth's surfacial deposits. About 20% of the surface area of India is covered with expansive soils (Mohan and Jain, 1961). These soils are subjected to shrinkage stresses during summer and undergo swelling during rainy seasons. The field movements associated with cyclic wetting and drying of expansive soils were monitored by many researchers (Atchison and Holmes, 1953; Freeman et al. 1992, to name a few). The main observations from the field were the amplitude of movement decreases with depth and there is a decrease in swelling with increasing number of cycles.

The cyclic swell-shrink experiments were done in the laboratory by many authors to simulate the field conditions. Laboratory studies show that the cyclic swell-shrink movements attain an equilibrium state after about four or five swell-shrink cycles (Ring, 1966; Subba Rao and Satyadas, 1987; Dif and Bluemel, 1991). The bandwidth of the cycles at the equilibrium stage is termed as equilibrium band width. The equilibrium band width increases with increase in liquid limit of the soil, decreases as the surcharge pressure increases but independent of sequence of wetting and drying and initial placement conditions for a given surcharge pressure (Day, 1994; Gangadhara, 1997; Tripathy, 1999).

Most of the desiccated expansive soils are overconsolidated soils. The shrinkage stresses developed during the drying cycle may make the soils overconsolidated. The degree of overconsolidation is often expressed in terms of preconsolidation pressure, which is the greatest vertical pressure the soil has experienced in the past. It is one of the most important properties of the soil, as it defines the boundary between stiff and soft deformation response of a soil under load. It can be expected that as a result of drying, the void ratio of the soil in the desiccation zone will approach the value corresponding to the shrinkage limit.

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To reach the void ratio corresponding to the shrinkage limit it may be necessary to apply consolidation pressures of the order of 1000 kPa and above (Yong and Warkentine, 1966; Fleureau et al. 1993). However studies on re-saturated desiccated soils do not always show evidence of these soils being subjected to very high stresses. Recent study indicated that swelling due to submergence in water greatly diminishes the effects of desiccation stresses so that the soils exhibit low apparent preconsolidation pressures (Robinson and Allam, 2008).

Though many studies are reported in the literature regarding the behaviour of expansive soils under repeated swell-shrink cycles, information about the magnitude of preconsolidation pressure due to desiccation is not well understood. This paper addresses this important issue through an experimental study on an expansive soil.

Experimental Program

Properties of Soil used

The expansive soil used in this investigation was taken from a site in Siruseri, near Chennai, Tamilnadu, founded at a depth of 1.5m from the ground level. The air dried natural soil was pulverized and sieved through 1 mm sieve. The index properties of the soil were determined as per Indian Standard Specifications (IS: 2720, 1991) and are listed in Table 1. The compaction characteristics were obtained by performing Standard Proctor Compaction tests. From the values of plasticity index and differential free swell, the clay can be classified as Clay of High Compressibility with high expansion potential (Holtz and Gibbs, 1956).

Table1 Properties of Soil used

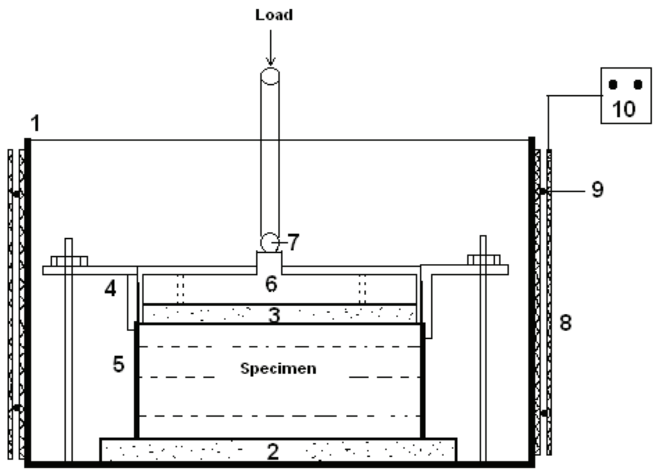
Properties	Value
Atterberg Limits:	
Liquid Limit (%)	69
Plastic Limit (%)	30
Shrinkage Limit (%)	8
Specific gravity	2.60
Grain size distribution:	
Clay (%)	69.5
Silt (%)	24.0
Sand (%)	6.5
Compaction test characteristics:	
Maximum dry unit weight (kN/m^3)	14.96
Optimum moisture content (%)	24
Differential free swell (%)	80

Sample Preparation

A known amount of soil was thoroughly mixed with water to a water content of 20% (water content at the dry side of optimum) and kept in an air tight plastic bag for about 24 hours, for moisture equilibrium. The tests were conducted in an oedometer ring of diameter 60 mm and height 20 mm. The samples were statically compacted in the oedometer cell to a thickness of 14 mm at a dry unit weight of 14.2 kN/m^3. A spacer was used to achieve the required thickness.

Cyclic Swell-Shrink Tests

The cyclic swell-shrink tests were carried out in a modified oedometer specially designed for this purpose. The schematic diagram of the set up is shown in Figure 1 and the photographic view of the test set up is shown in Figure 2. The set up consists of a fixed ring oedometer cell placed inside a stainless steel container (Outer jacket). To facilitate quicker shrinkage, an elevated temperature of 40 ± 5 ^{0}C was maintained during the drying process. The outer face of the stainless steel jacket holds a 1kW capacity nichrome coil tightly sandwiched between two asbestos sheets. The air temperature inside the system is monitored by a thermocouple which is inserted in to the outer jacket. The thermocouple is connected to a thermostat, which controls the temperature of the whole system to the required value.



1 – Outer stainless steel jacket
2 – Bottom porous stone
3 – Top porous stone
4 – Outer ring
5 – Specimen ring (Oedometer ring)
6 – Pressure pad
7 – Pressure ball
8 – Thermal insulator
9 – Nichrome coil
10 – Thermostat

Fig. 1 Modified Oedometer for Cyclic Swell-Shrink Tests

The sample prepared as per the procedure explained above was placed between the top and bottom porous stones inside the outer jacket of the set-up. Then the sample was loaded with desired surcharge pressure through the lever arm arrangement in the oedometer frame. The sample was inundated with water and sufficient time was given for the sample to swell. After the equilibrium swelling, the sample was allowed to shrink in an elevated temperature of 40 ± 5 ^{0}C by the coil system till equilibrium is achieved.

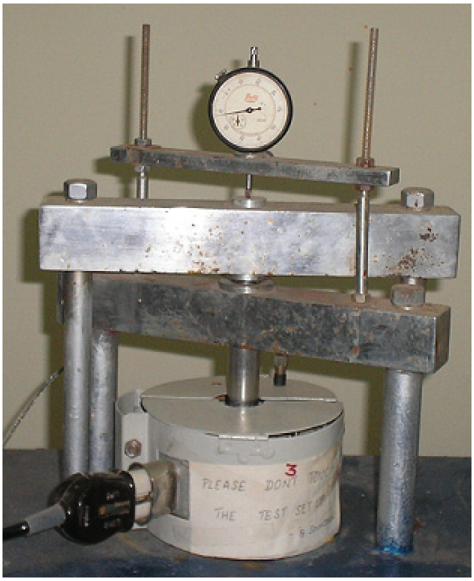


Fig. 2 Photographic View of Cyclic Swell Shrink Test Set-Up

The vertical movement of the soil sample inside the oedometer ring is monitored by the dial gauge during both swelling and shrinkage of the soil sample. Time taken for each cycle for full swelling and full shrinkage were 5 days and 15 days, respectively. This process of wetting and drying was repeated till equilibrium value of swell-shrink has been observed.

The cyclic swell-shrink tests were conducted for surcharge pressures of 6.25, 12.5, 25, 50, 100 and 200 kPa. The cyclic swell-shrink movements attain equilibrium after about 5 cycles. After fifth cycle of shrinkage, the samples were inundated with water and allowed to swell. The samples after reaching full swelling were unloaded to a seating pressure of 6.25 kPa and then increment loading consolidation tests were conducted to a maximum pressure of 800 kPa. A load increment ratio of 1.0 was adopted for the consolidation test.

The wet density and final moisture content of the dismantled samples were determined after the test. For the determination of shrunken void ratio of the samples, the samples were dried in the oven at about 60^0 C. The void ratio of the dried sample was determined by mercury displacement method.

Results and Discussions

The cyclic swell-shrink movements of the identical samples under different surcharge pressures are monitored till equilibrium movement occurs. The axial strain (ε_a) values were computed from:

$$\varepsilon_a = \frac{(H - H_i)}{H_i} \times 100 \quad (1)$$

where,

H – Thickness of the sample for that particular cycle

H_i – Initial thickness of the sample

Figure 3 shows typical plot of time versus axial strain of a sample under a surcharge pressure throughout the entire swell-shrink cycles. Number of cycles, defined as one full swelling and full shrinkage, is also marked in the figure. One swelling cycle took about 5 days whereas the shrinkage took about 15 days. The total time taken for completing one test is about 6 months. The number of days to reach the equilibrium swelling or shrinkage also depends on the surcharge pressure. Higher the surcharge pressure lesser is the time required for complete swelling and shrinkage.

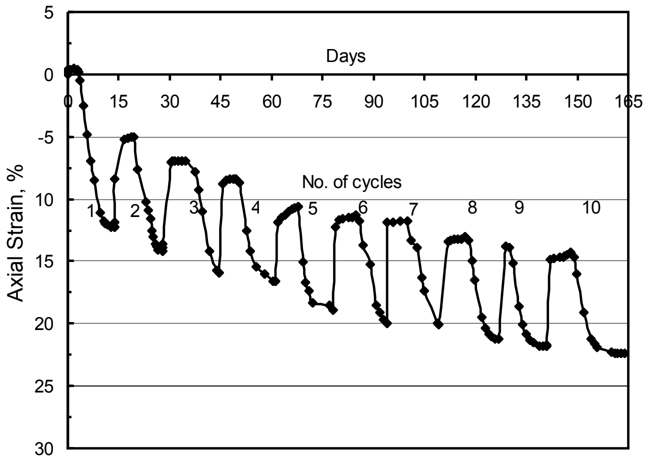


Fig. 3 Typical Axial Strain with Time for Sample Under 100 Kpa Surcharge Pressure

The variation of axial strain with number of cycles for the samples under different surcharge pressures is plotted in Figure 4. The movements attain equilibrium after about 4 to 5 cycles irrespective of the surcharge pressure. However, the position of the cyclic movement depends on the surcharge pressure. Similar observations were reported in the literature (Gangadhara, 1997; Triapathy, 1999, to name a few). For higher surcharge pressures, the movements shifted down to the datum line (zero axial strain) as shown in Figure 4.

The sample strain within the equilibrium swollen and shrunken cycle is termed as equilibrium band width (EBW) as marked in Figure 4. The equilibrium band width depends on factors like liquid limit, surcharge pressure and soil type (Day, 1994; Gangadhara, 1997). Figure 5 shows the variation of equilibrium band width with surcharge pressure on the sample. From Figure 5, it is clear that the equilibrium band width decreases with increasing surcharge pressures on the sample. This finding is in agreement the studies of Subba Rao and Satyadas (1987), Dif and Bluemel (1991), Gangadhara (1997) and Tripathy (1999). It is also noted that the plot of equilibrium band width with surcharge pressure may be approximated as a straight line in EBW - log σ_v' plot.

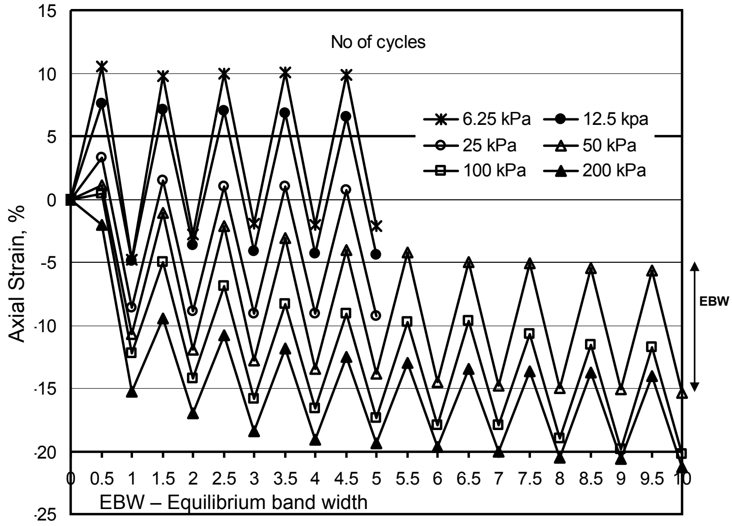


Fig. 4 Variation of Vertical Strain with Surcharge Pressures

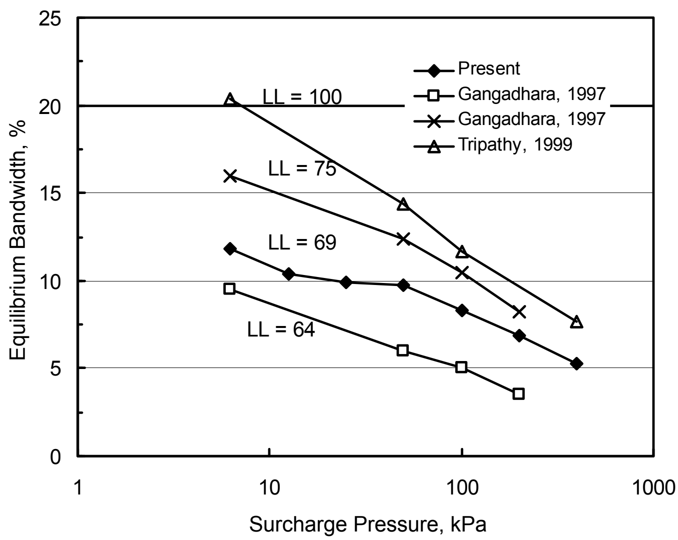


Fig. 5 Variation of Equilibrium Band Width with Surcharge Pressure

The variation of equilibrium band width with liquid limit of the soil is also given in Figure 5. The experimental data points obtained in the present study are also compared with those reported in the literature. From the comparison, it is observed that the position of equilibrium band width line depends on the surcharge pressure and also liquid limit of the soil. With increase in liquid limit of the soil, the equilibrium band width line shifted upwards and vise versa.

In all the cases, it was observed that the displacements in the second cycle (swollen or shrunken) are higher than that at any other cycle. Thereafter, the displacements are continuously decreased and were found to be constant after 4 or 5 cycles. The fatigue of swelling was observed after second cycle as shown in Figure 6. This fatigue phenomenon is also reported in the literature (For example: Chen, 1988; Dif and Bluemel, 1991, Al-Homoud et al, 1995). The reduction in percent swell may be due to the aggregation of clay particles upon wetting and drying (Al- Homoud et al, 1995).

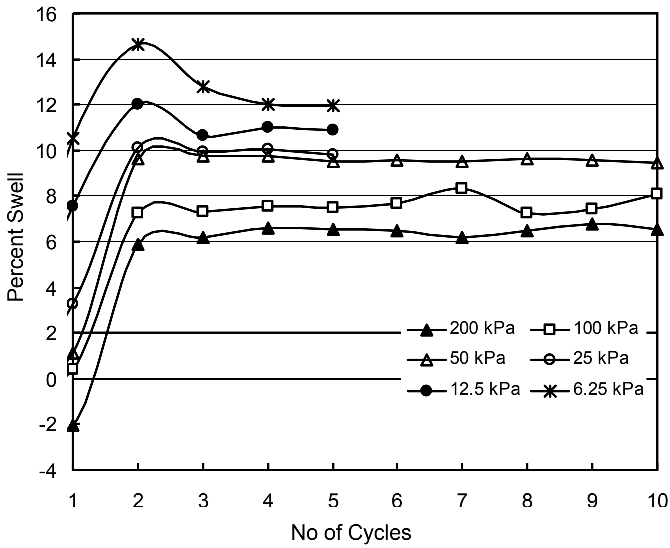


Fig. 6 Fatigue of Swell with Cycles

The void ratio of the samples at different surcharge pressures were back calculated from the final water content and final thickness of the sample. The shrunken void ratio of the desiccated sample (sample subjected to 4 or 5 swell shrink cycles) pieces were determined by mercury displacement method and the equilibrium shrunken void ratio of the sample was found by approximating volumetric shrinkage equals the vertical shrinkage. The results are shown in Figure 7. The equilibrium swollen and shrunken void ratio lines are almost straight lines and the shrunken void ratio of the pieces are almost equal to the shrinkage limit void ratio of the soil. These results may be used for the determination of equilibrium movement of any structure founded in the expansive soil under a surcharge pressure.

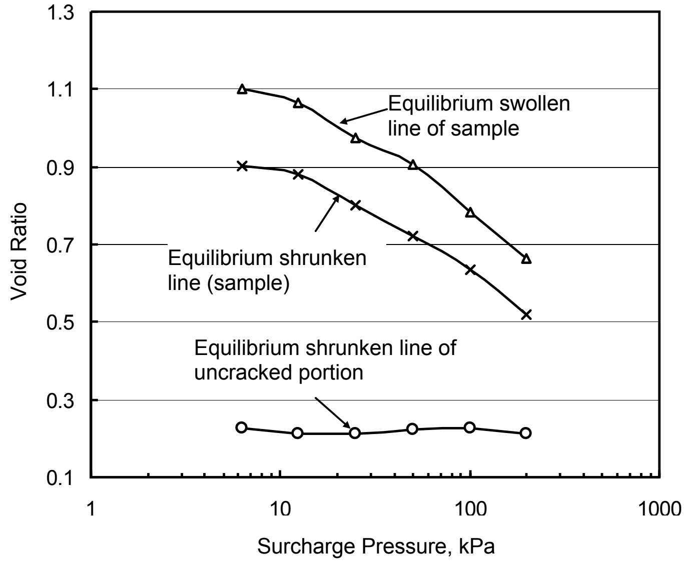


Fig. 7 Equilibrium Swollen and Shrunken Void Ratio

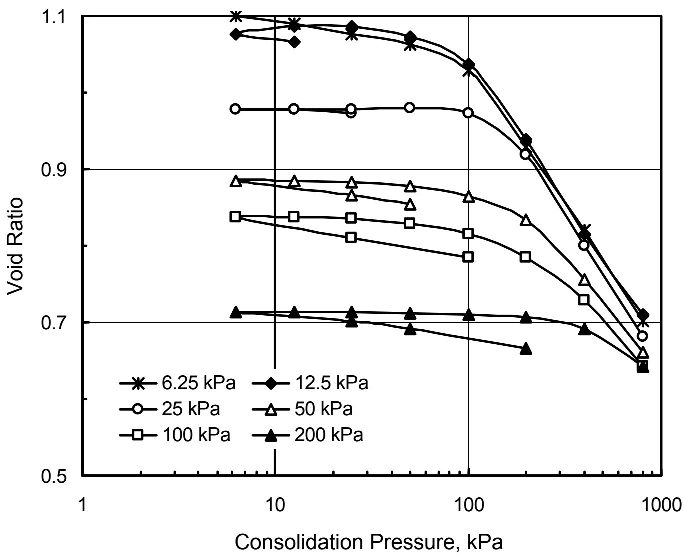


Fig. 8 Consolidation Data for Desiccated Samples under Different Surcharge Pressures

Consolidation Behaviour of Desiccated Sample

The consolidation test data of the desiccated sample is used for the determination of preconsolidation pressure and overconsolidation margin of the desiccated sample. The e-log σ_v' plot for all the samples are shown in Figure 8. The plots clearly show that the samples subjected to wetting and drying cycles depict overconsolidation behaviour. The preconsolidation pressures (σ'_c) of these samples were determined using the log (1+e) versus log σ_v' plot (Butterfield, 1979; Sridharan et al, 1991).

The consolidation curves shown in Figure 8 are re-plotted as log (1+e) versus log σ_v' plot in Figure 9. The plots are bilinear and the intersection point is the preconsolidation pressure. The values of preconsolidation pressure under different surcharge pressures are listed in Table 2. It is seen that the preconsolidation pressure increases with increase in surcharge pressure. This indicates that the preconsolidation of desiccated expansive soils increases with depth.

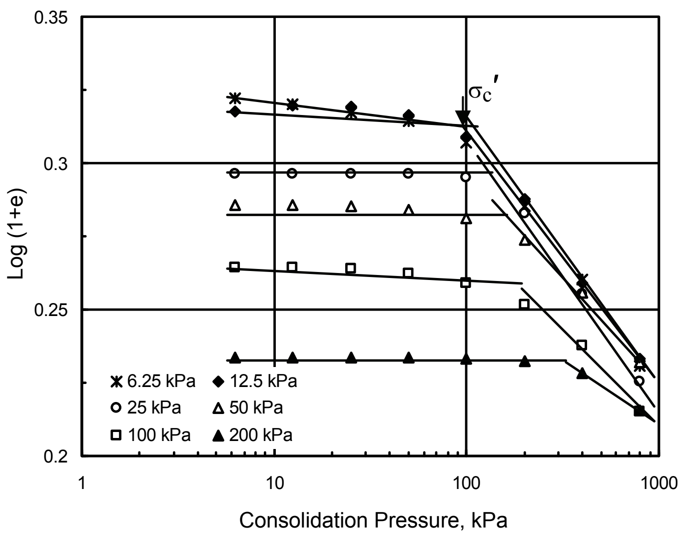


Fig. 9 Determination of Preconsolidation Pressure of Desiccated Samples under Different Surcharge Pressures

Another parameter over consolidation margin (σ'_m), which is the difference between the preconsolidation pressure and the effective vertical pressure, is also an important property of the soil. Over consolidation margin is approximately constant throughout in a stratum with common geologic origin (Coduto, 2003). Hence it is useful to compute preconsolidation pressure (σ_c') at other depths (in soil strata with the same geologic origin).

Hence the over consolidation margin and the over consolidation ratio, which is the ratio of preconsolidation pressure and effective vertical pressure are also listed in Table 2 besides the preconsolidation pressure of samples. From the table, it is observed that the over-consolidation margin is approximately constant at a value of about 100 kPa.

Table 2 Pre-consolidation Pressures of after Cyclic Samples

Vertical Pressure, kPa	Pre-consolidation Pressure, kPa	Over Consolidation Ratio	Over consolidation Margin, kPa
6.25	100	16	94
12.5	109	8.7	97
25	138	5.5	113
50	158	3.2	108
100	203	2.0	103
200	315	1.6	110

Conclusions

From the experimental study reported in the paper, the following conclusions are drawn:

- Equilibrium band width occurs after 4 to 5 cycles of wetting and drying and it decreases with increase in surcharge pressure almost linearly in the EBW versus log σ_v' plot..
- The consolidation behaviour of desiccated expansive soil is similar to overconsolidated soils.
- The preconsolidation pressure of desiccated expansive soil depends on the surcharge pressure. It increases with increase in surcharge pressure on the sample. Thus the desiccation induced preconsolidation pressure is similar to overburden pressure in the geological past.
- The overconsolidation margin of desiccated expansive soil is almost constant of about 100 kPa and can be used to determine the preconsolidation pressure of sample at any depth of the same geologic originated sample.

Notations

H – Thickness of the sample for the particular cycle

H_i – Initial thickness of the sample

EBW – Equilibrium Band Width

LL – Liquid limit

e – Void ratio

ε_a – Axial strain of the sample

σ_v' – Effective vertical pressure

σ'_c – Preconsolidation pressure

σ'_m – over consolidation margin

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