Swell-Shrink Behaviour of Expansive Soils – Geotechnical Challenges

K.S. Subba Rao[†]

Expansive Soils

E xpansive soils are found in the arid and semi-arid regions of the world and are in abundance where the annual evaporation exceeds the precipitation. Hot climate and poor drainage conditions are usually associated with the formation of these soils. The colour of these soils varies from deep black to grey and sometimes even reddish or yellowish.

In India, these soils are generally called as Black cotton soils (or Regur) and cover about 20% of the total land area. They are formed in the states of Maharastra, Madhya Pradesh, Gujarat, Andhra Pradesh, Karnataka and Tamilnadu. Apart from India, Africa, Australia, Israel, USA, Jordan, Ethiopia etc., also possess vast tracts of such soils.

Expansive soils are residually derived from the gneiss, basalt, basic volcanic ash, calcarious aluminum and sedimentary rocks containing calcarious shales, lime stones, slates and sand stones (Humad, 1987). The underlying bedrock of black cotton soil to a large extent is basaltic or traps. Black cotton soil forms due to the subaerial weathering of the basalts in-situ and subsequent admixture of the weathered products with iron and organic matter (Wadia, 1975).

The thickness of these soils varies from 30 cm to 15 m, while the composition of the soil shows considerable variation with different depth horizons, especially in its clay content and lime segregation. Wadia (1975) has reported that the clay fraction of black cotton soil is very rich in silica

† Professor and Chairman, Department of Civil Engineering, Indian Institute of Science, Bangalore – 560 012, India.

(60%) and iron (15%) with only 25% of alumina. Differential thermal analysis and X-ray diffraction pattern analysis (Roy and Char, 1969; Sridharan and Venkatappa Rao, 1973; Lunkad, 1977; Katti, 1979) have shown that montomorollinite is the predominant clay mineral in black cotton soil. Other clay minerals Illite and Kaolinite are present in smaller quantities. The specific gravity of black cotton soil ranges from 2.7 to 2.9 (Katti, 1975; Sridharan and Venkatappa Rao, 1973; Subba Rao and Satyadas, 1980; Sridharan and Rao, 1982).

Field Movements

Soils of expansive nature are problematic to the civil engineering structures because of their large volume changes due to the variations of water content. During rainy season, the soil within the active zone heaves and during summer season, it shrinks. Soil heaves even if the moisture ingress were to take place due to other environmental changes like leaks in plumbing work, drainage, lawn irrigation etc., or if any stress release were to take place. Similarly, soil shrinks if moisture content were to reduce due to climatic effects, withdrawal of water by tree roots, local heating due to central heating systems, such as boilers, furnaces etc.

The field observations made by several researchers under uncovered areas (Aitchison and Holmes, 1953; Holland and Lawrence, 1980) and under covered areas (Dinesh Mohan, 1958; Johnson, 1980; Justo et al., 1985; Trevisan, 1987; Retmal et al., 1987; Xinfang et al., 1987; Sorochan, 1991) have established the cyclic upward and downward movements of expansive soils due to alternate wetting and drying cycles.

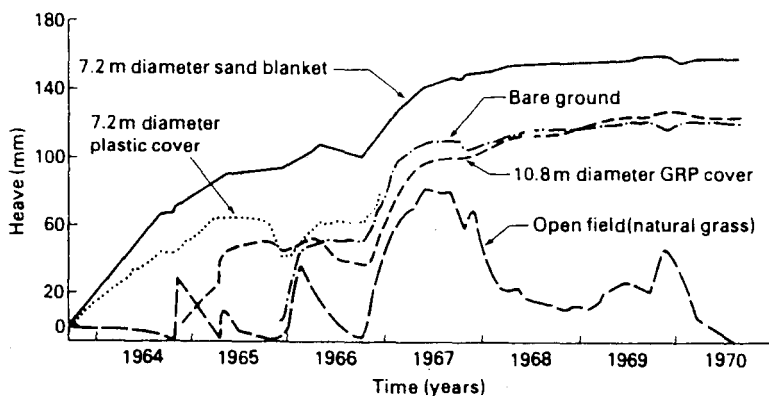Some typical field movements are shown in Figs.1, 2 and 3. The

FIGURE 1 : Movements of the Ground Surface under Various Conditions of Surface Cover (Williams and Pidgeons, 1967)
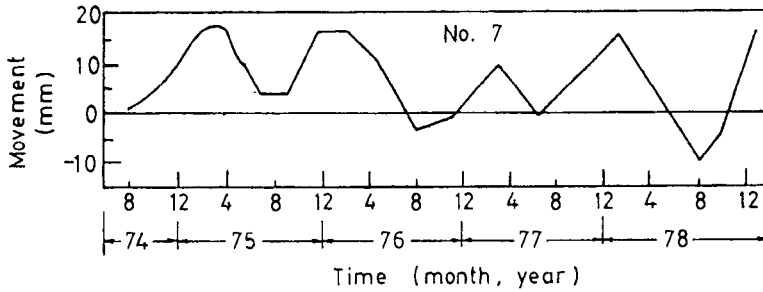
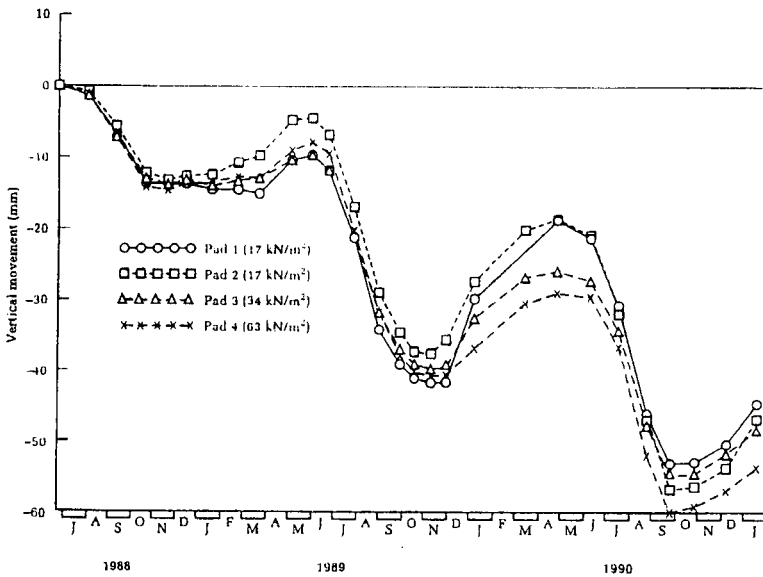FIGURE 2 : Foundation Movements with Time (Haung Xiling, 1987)

FIGURE 3 : Seasonal Movement of 1m Square × 2m Deep Loaded Pad
Foundations (Freeman et al.)

observations indicate the ground movements and also the foundation
movements recorded over some years. The ground movement cycles generally
correlate with variations in rainfall and evaporation. Depending upon the depth
from the surface, time lag occurs for swelling with precipitation and shrinkage
with evaporation. The behaviour of foundation soil is observed to be similar
to that of soils under covered areas. The ground movements decrease with
increasing depth and are confined within the active zone depth, which usually
varies from 4 to 6m.

When an expansive soil is used as a construction material or as a
foundation base, it could be subjected to either swelling or shrinkage
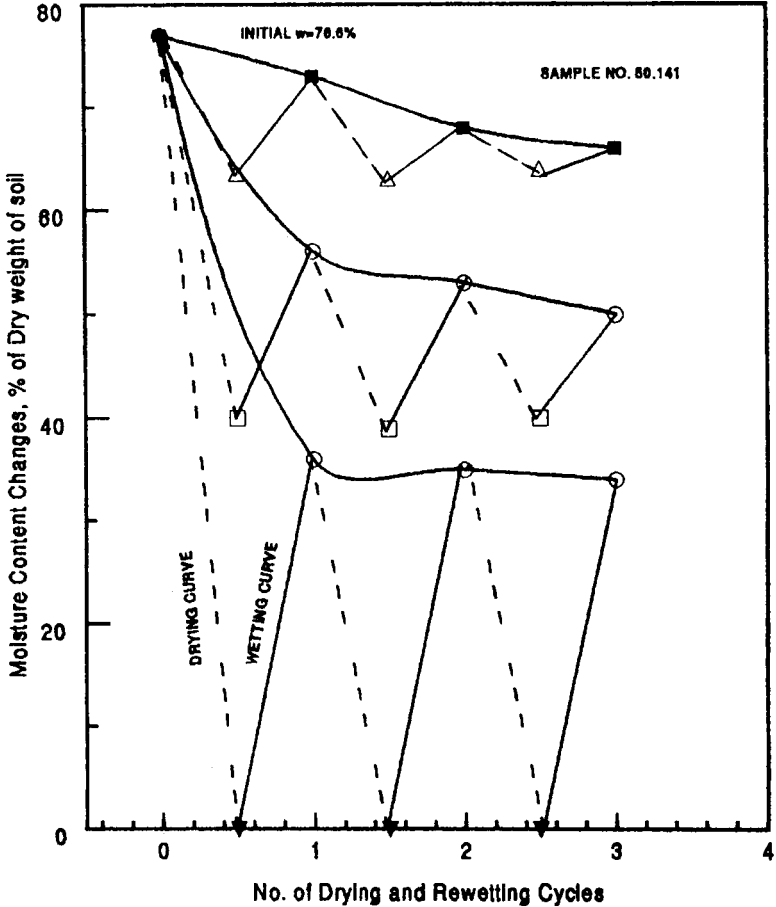first, depending on the period of construction activity. If construction

FIGURE 4 : Effect On Drying and Re-Wetting on the Ultimate Moisture
           Content of Ottawa Clay (Warkentin and Bozozuk, 1961)

activity were to start after the rainy season, the initially moist soil would
be first subjected to shrinkage during the dry season. Subsequent to
drying, the shrunken soil will experience wetting during the rainy season,
so that the sequence is drying- wetting process. On the other hand, if
construction activity were to start in the dry period, the resulting sequence
would be wetting-drying process. The overall movements depend on how
the sequence gets started.

The extent of vertical movement varies depending upon the location of
the point from the surface, type of soil, whether covered or not, surcharge
imposed on it, etc. These movements would be occurring over a range, which
remain steady and would be in equilibrium under a particular environment.
When this steady state is altered, through climatic changes or through other
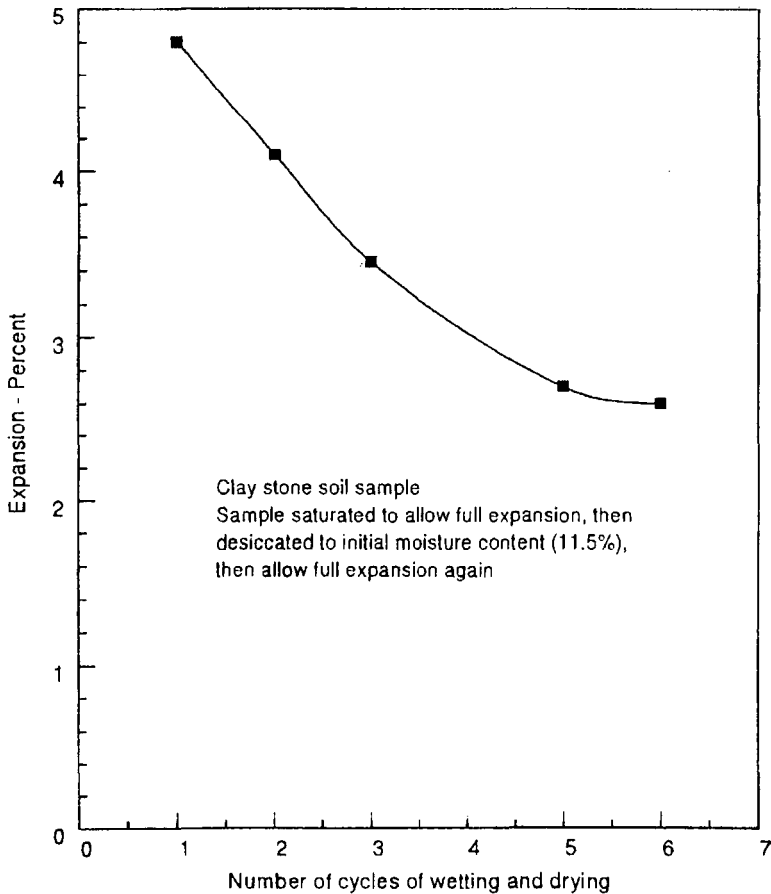
The graph shows Expansion - Percent (y-axis, 0 to 5) versus Number of cycles of wetting and drying (x-axis, 0 to 7). A declining curve starts near 4.85 at cycle 1, drops to about 4.1 at cycle 2, to about 3.5 at cycle 3, levels to about 2.7 at cycle 5, and about 2.6 at cycle 6.

Clay stone soil sample
Sample saturated to allow full expansion, then
desiccated to initial moisture content (11.5%),
then allow full expansion again

FIGURE 5 : Fatigue of Swelling (Chen, 1965)

means like, when a structure is built over the soil, involving activities like excavation, loading, etc, the soil foundation system will again have to reach a level of equilibrium. This normally takes place over a few seasons.

Earlier Laboratory Investigations

Controlled laboratory tests on soil specimens have great advantage in throwing light on the swell-shrink behaviour of expansive soils, since they afford parametric studies. Earlier studies made by Warkentin and Bozuzuk (1961), Chen (1965) and Ring (1966), showed that the soils when subjected to cyclic wetting and drying showed signs of "fatigue" after each cycle. The net decrease in the swollen volume of the specimen becomes smaller and smaller with each cycle and after a few cycles the swollen volume reaches a steady state.
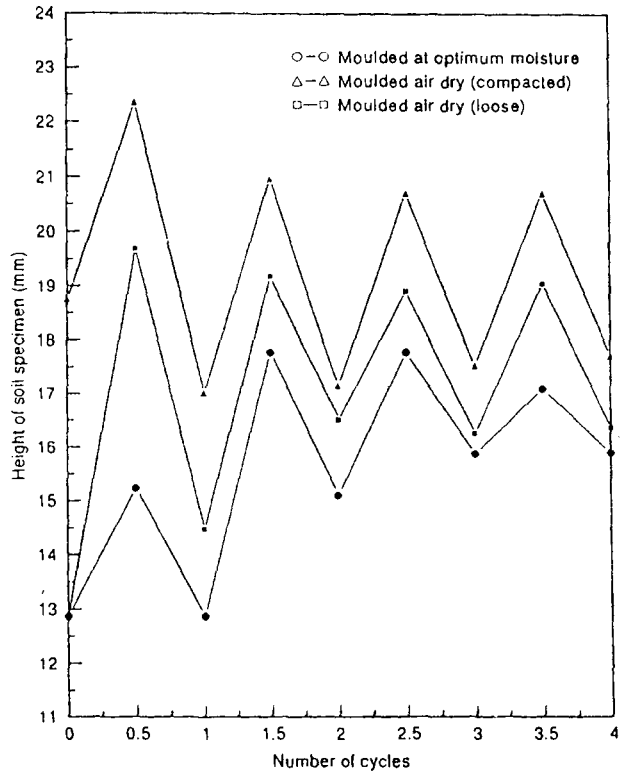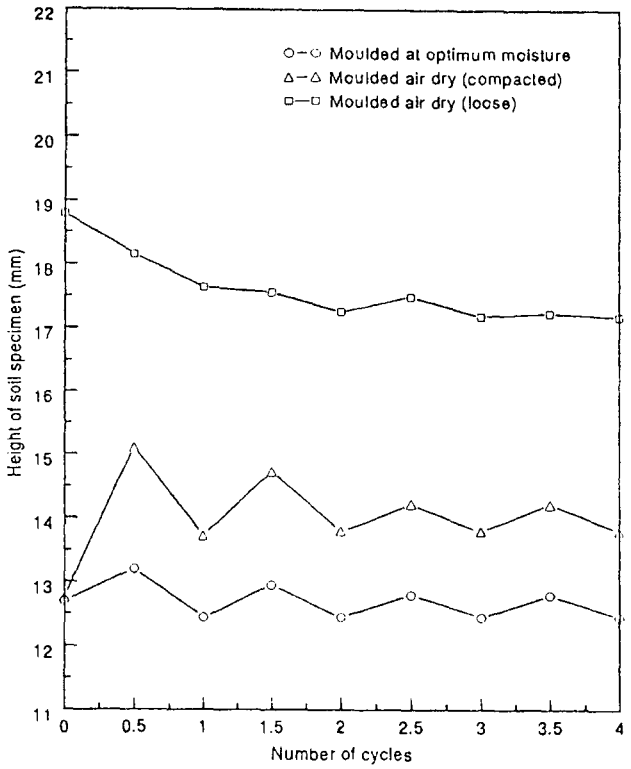
FIGURE 6 : Height Changes under Alternate Wetting and Drying under 0.25 psi Surcharge Specimens of Cecil and Iredell Clay (Ring, 1966)

Warkentin and Bozozuk dried the specimen to particular water content, swelled it fully and did the cyclic tests maintaining the shrunken water content constant. Fig.4 shows the results. Chen allowed full expansion and desiccation to initial moisture content in each of the cycle (Fig.5). In the experiments conducted by Ring (Fig.6), the specimens were allowed to fully swell and fully shrink in each of the cycles from initial air-dry conditions.

Following the above initial studies, a number of researchers have conducted alternate wetting and drying experiments. Laboratory investigations fall into two groups depending on degree of shrinkage experienced by the expansive soil specimens during drying. One group of researchers (Chu and Mou, 1973; Chen and Ma, 1987; Subba Rao and Satyadas, 1987; Al-Homoud et al., 1995) performed partial drying experiments by restricting the expansive soil specimens to shrink to pre-determined levels of moisture content or specimen thickness. The other group of investigators (Popescu, 1980; Osipov et al., 1987; Dif and Bluemel, 1991; Day, 1994) fully shrunk their expansive soil specimens. These laboratory investigations suggested that by repeatedly subjecting the expansive soil specimens to full swelling-partial shrinkage cycles, their vertical swell potentials reduce to less than half of their as-compacted values. Comparatively, exposure of expansive soils to full swelling-full shrinkage cycles can almost double their swell potentials. In both the cases, the vertical swell potentials reached an equilibrium state after about three to five cycles. However, certain initial conditions prolong the number of cycles needed for equilibrium stage. For a black cotton soil (BC) specimen of initial water content 15% and void ratio 1.127, the movements did not stabilise even after 10 cycles (Satyadas, 1982) as seen in Fig.7. Full swelling and partial shrinkage experiments conducted by Mahesh Kumar (1998), showed that black cotton soil having initial conditions of γ_d = 1.28 Mg/m^3, w = 23.4% and S$_r$=57%, (point on the dry side of standard proctor compaction curve) required 15 cycles to equilibrate (Fig.8).

Scope

The codal stipulations (IS:2720 Part 41-1977, ASTM Designs D 4546-90) mention that the laboratory experiments need to simulate the soil specimens to cyclic wetting and drying process, prior to evaluating the swell potentials under the anticipated foundation pressures.

In order to better understand the behaviour of expansive soils, it becomes necessary to examine how the soil undergoes the swell-shrink movements, the details of movements like the highest swollen level and the lowest shrunken level and the equilibration bandwidth, which is the movement between the swollen and shrunken states at equilibrium. It is also necessary to know how the initial placement conditions, the swell-shrink patterns and the surcharge levels affect the swell-shrink behaviour.
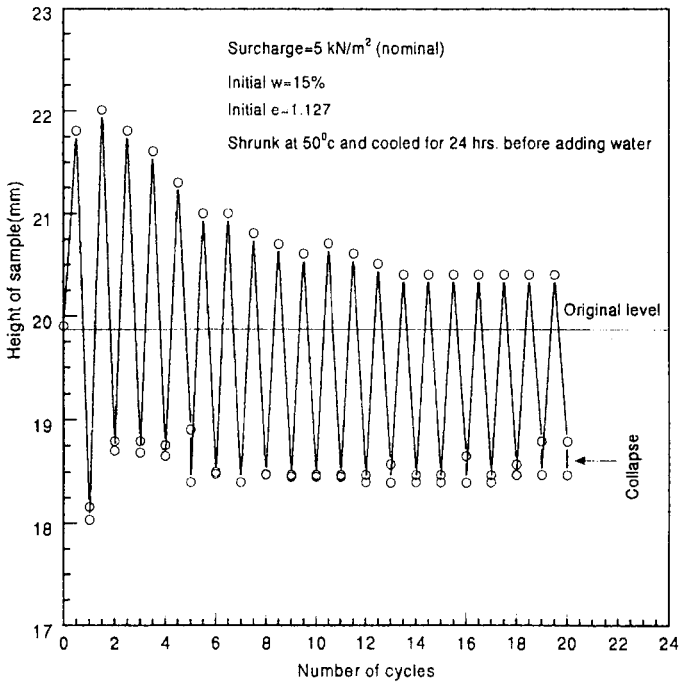
FIGURE 7 : Swell-Shrink Behaviour of BC Soil Showing Large Number of
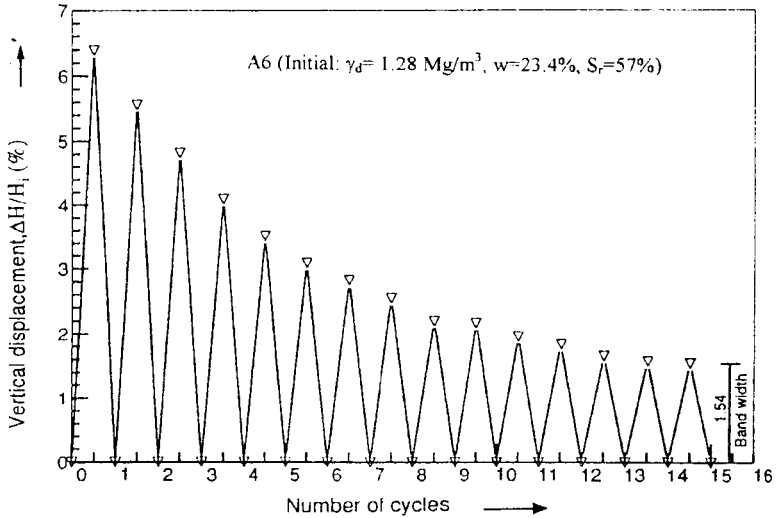Cycles to Reach Equilibrium under Full Swelling-Full Shrinkage Pattern
(Satyadas, 1982)

FIGURE 8 : Swell-Shrink Behaviour of BC Soil Showing Large Number of
Cycles to Reach Equilibrium under Full Swelling-100% Shrinkage Pattern
(Mahesh Kumar, 1998)

In the laboratory experimentation, one has to choose appropriately the swell-shrink patterns in the test, based on the knowledge of the field suction or moisture content variation with depth. Soil can be expected to experience full swelling in the field atleast in the top layers. However the shrinkage of soil in the field rarely goes unhindered to its full value except during a prolonged drought period. With depth, the most likely patterns will be partial swelling and partial shrinkage in each cycle. However for convenience and also to obtain the conservative estimate of swell potential, the patterns that are adopted are (i) full swelling-full shrinkage and (ii) full swelling-partial shrinkage.

It is known that soil will primarily heave in vertical direction in the field, as lateral swell is restricted by the adjacent soil mass (Jennings and Kerich, 1962). However the above may not be true for (i) expansive soils that undergo severe fissuring on drying, (ii) soils in slopes and (iii) retaining wall structures subjected to lateral pressures (Gramko, 1974). Accordingly, to make the laboratory swell measurements relevant to all field situations, laboratory swell data are analysed both in terms of vertical and volumetric strains.

It will be of interest to know how in each cycle at the swollen or shrunken level, the moisture content and dry density values vary, also how the shear strength varies with cycles. These studies together with time rate of development of swelling or shrinkage will help in answering the reversibility or otherwise of swelling and shrinkage process. From the results of extensive investigations on the laboratory compacted specimens, started at IISc, some 20 years ago, the basic issues in the swell-shrink behaviour of expansive soils will be addressed in the following sections. Besides, the widely used method of cushioning the expansive soil with a cohesive non-swelling soil (CNS) layer will also be critically examined.

Generalised Movement Modes

The nature and extent of vertical movement depend on several factors like the type of soil, whether covered or not, surcharge imposed on it, depth of the point from the surface, climatic condition etc. Xiling (1987), in a broad sense classified these movements into three categories:

        i)   Uprising

        ii) Descending

        iii) Uprising -- descending

However, for in-depth understanding of the cyclic behaviour of expansive soils, five modes have been suggested here based on extensive

laboratory investigations and on careful study of field movements. The suggested five classifications are shown in Figs.9 to 13, herein called types A, B, C, D and E. Out of these five modes two modes refer to the uprising and another two refer to the descending modes.

The nomenclatures used in these figures are as follows.

1. *Highest Swollen Level*: It is the highest level to which the specimen swells in any of the swell-shrink cycles.

2. *Equilibrium Swollen Level*: It is the swollen level recorded at equilibrium state, which usually occurs after a few swell-shrink cycles.

3. *Equilibrium Shrunken Level*: It is the shrunken level of the specimen at equilibrium state, which usually occurs after a few swell-shrink cycles.

4. *Operating Middle Level*: It is the middle level between equilibrium swollen level and equilibrium shrunken level.

5. *Equilibrium Bandwidth*: It is the bandwidth of vertical displacement at equilibrium state between equilibrium swollen level and equilibrium shrunken level.

6. *Initial Reference Level*: It is the initial level of the specimen with respect to which all measurements are made.

7. *Lowest Shrunken Level*: It is the lowest level to which the specimen shrinks in any of the swell-shrink cycle.

8. *Operating Displacement*: It is the level difference between operating middle level and initial reference level.

9. *Extreme Displacement*: It is the extreme vertical displacement recorded by the specimen.

In type A mode (Fig.9), the initial reference level is below all other levels. In type B mode (Fig.10), the lowest displacement level is below the initial reference level, but all other levels are above the initial reference level. In type C mode (Fig.11) the initial reference level falls within the equilibrium bandwidth. In type D mode (Fig.12) the highest displacement level is above the initial reference level, but the equilibrium swollen level will be below the initial reference level. In type E mode (Fig.13). The initial reference level is above all the other levels.
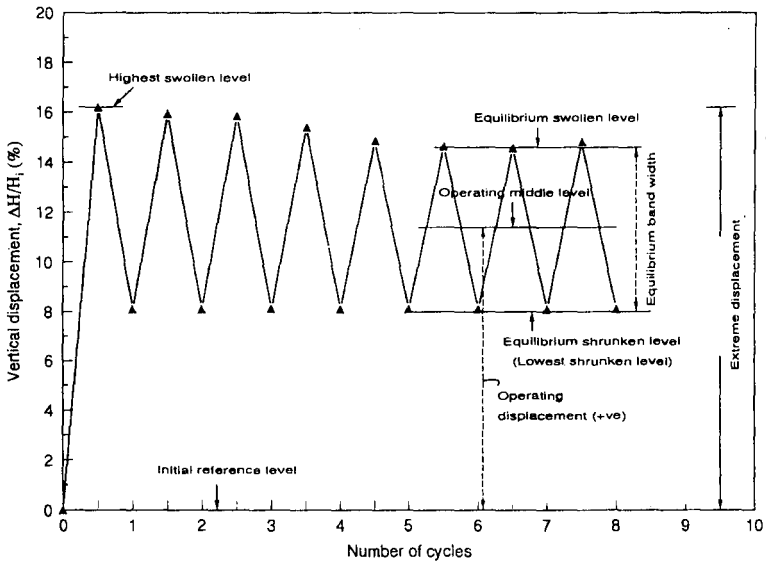
FIGURE 9 : Swell-Shrink Movement (Type A), with All Movements above
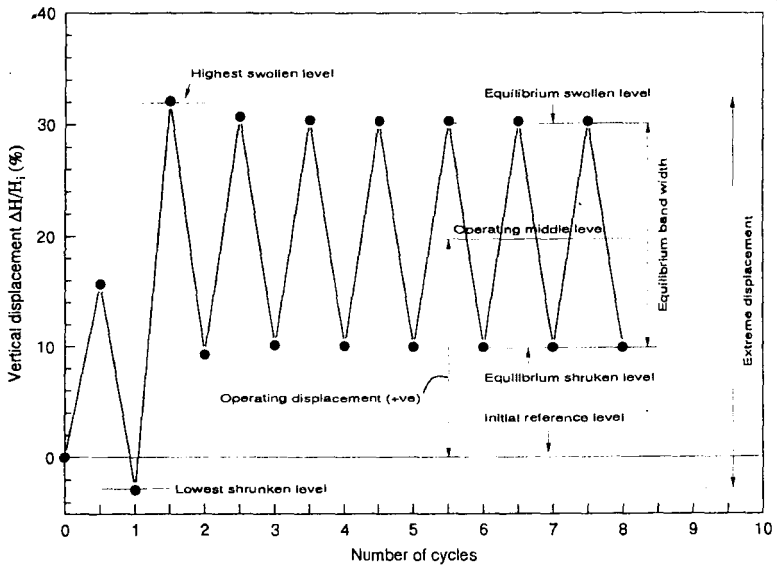the Initial Reference Level

FIGURE 10 : Swell-Shrink Movement (Type B), with Equilibrium Bandwidth
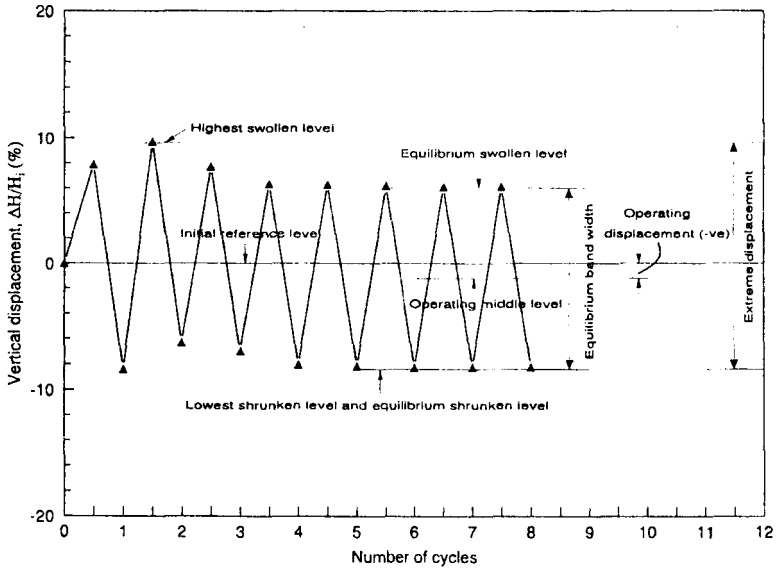above the Initial Reference Level

FIGURE 11 : Swell-Shrink Movement (Type C), with Equilibrium Bandwidth Spread over the Initial Reference Level
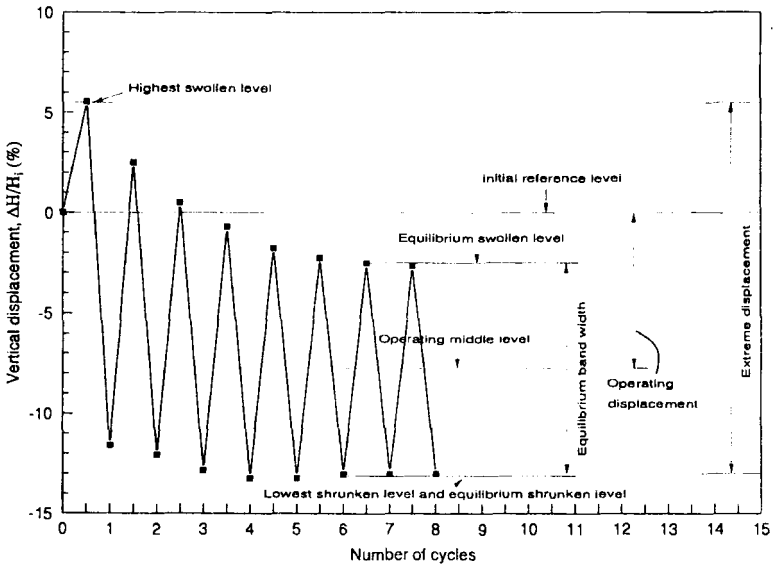

FIGURE 12 : Swell-Shrink Movement (Type D), with Equilibrium Bandwidth Entirely below the Initial Reference Level
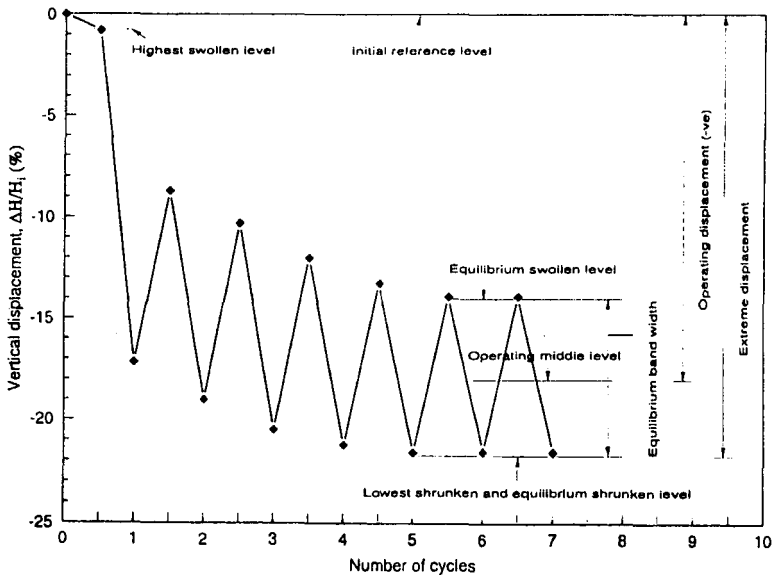
FIGURE 13 : Swell-Shrink Movement (Type E), with All Movements below the Initial Reference Level

The swell-shrink behaviour of any soil can span across all types of modes A to E, depending on several factors like the initial conditions, surcharge levels, swell-shrink patterns etc. A dense system with low initial water content usually show Type A mode. If the surcharge level is so high as to suppress the swell potential, Type E mode will result. For the same density, if the initial water contents were to increase, mode can change from A to C. Similarly, a change from mode C to E can be achieved by changing the surcharge pressure.

In design and performance of foundations in expansive soils or earth structures on expansive soils, a clear understanding of different modes and all levels of movements become necessary for any rational design. As of now this is a domain of considerable uncertainty.

Equilibrium Bandwidth

The results of cyclic experiments are plotted in terms of vertical displacement (%), defined as $\Delta H/H_i$, where ΔH is the change in thickness of specimen from the as-compacted state to the swollen or shrunken state during the first cycle of wetting or drying. During the subsequent wetting and drying cycle ΔH refers to the change in the height from the swollen state to the shrunken state or from the shrunken state to the swollen state of the specimen. The denominator H_i is the initial (as-compacted) placement thickness of the specimen.

Some of the results are also analysed in terms of volume change (%), defined as $\Delta e/(1+e_i)$, where, Δe refers to the change in void ratio during each swelling or shrinkage cycle and e_i is the initial or as-compacted void ratio of the specimen.

To illustrate the concept of bandwidth, Fig.14 plots the variation of the vertical displacements with time during each swelling and shrinkage cycle of an expansive soil specimen subjected to alternate cycles of wetting and drying in the laboratory. It can be seen from this figure that the vertical movements of the specimen vary initially during the first two cycles of wetting and drying. After four cycles of wetting and drying, the movements operate between near constant limits. This movement during "equilibrium" state is termed as the 'band width'. The results of swell-shrink experiments can also be plotted as shown in Fig.15. Fig.15 plots the maximum vertical displacements at the end of each swelling and shrinkage cycle. Examination of Fig.6 also clearly brings out the equilibrium movement state and the existence of bandwidth. However, the earlier focus was only on phenomenon of fatigue.

Subba Rao and Satyadas (1987), Al-Homoed et al. (1995), based on their experimental investigations confirmed the existence of bandwidth of an expansive soil subjected to alternate cycles of full swelling and partial shrinkage. Subba Rao and Satyadas (1987) allowed the laboratory compacted soil specimens to swell fully but controlled during each cycles of drying the shrinkage magnitudes to different percentages of the first swollen height, viz., 25, 50 and 75%. The magnitude of bandwidth was observed to reduce with decrease in the amount of drying.
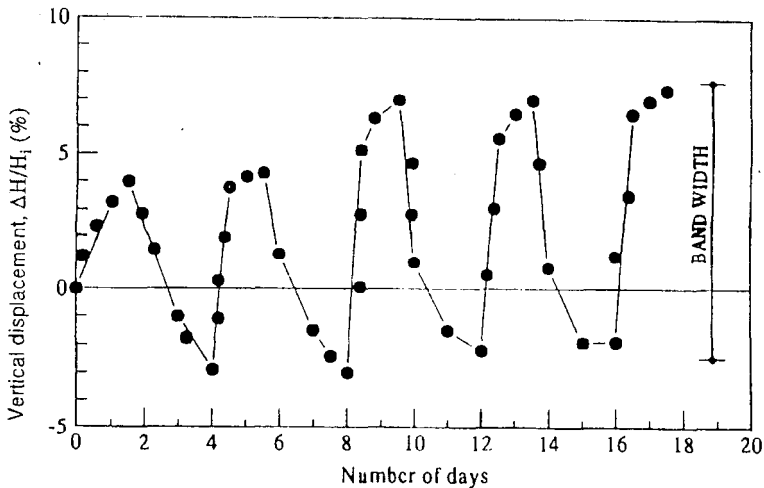

FIGURE 14 : Typical Plot of Vertical Displacement with Time During Each Wetting and Drying Cycle
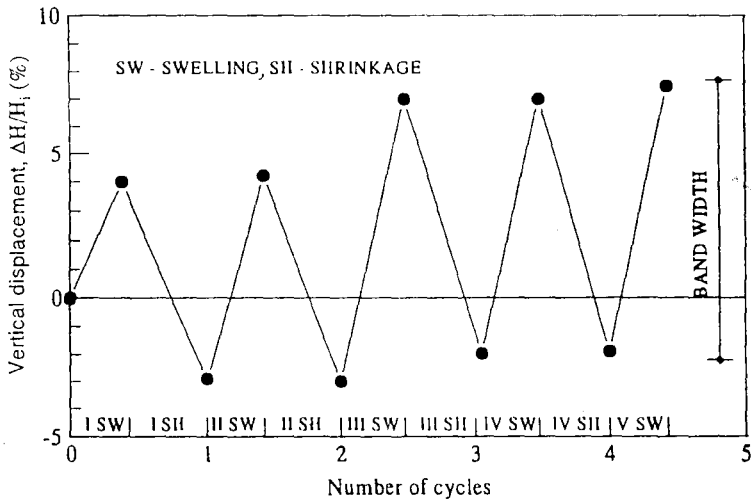
FIGURE 15 : Typical Plot of Vertical Displacement during Wetting-Drying Cycles

To examine the influence of variations in the initial dry density and compaction water content on equilibrium band width, Subba Rao et al. (1998) selected three soils, with liquid limit of 64%, 75% and 103% respectively. Compacted specimens were prepared with a wide range of initial dry densities and molding water contents. At each compaction water content, the initial dry densities of the specimens were varied. From water contents so chosen for each soil, the specimens were statically compacted into standard consolidation rings to a thickness of 13.5mm. The specimens were allowed to swell under a surcharge of 6.25 kN/m². The modified oedometer assembly had provision to maintain an elevated temperature of 40°C during each drying cycle. Each cycle comprising of full swelling and full shrinkage took 5 days (2 days for wetting and 3 days for drying). During each wetting part of the cycle, the shrunken specimen regained its original diameter (76mm) with closure of shrinkage cracks. The vertical displacements of the soil specimens became nearly constant after 3 or 4 cycles of wetting and drying. The cyclic experiments were hence terminated after four and half cycles.

Figure 16 plots the equilibrium bandwidth for a wide range of compaction water contents and dry densities. Figure shows clearly that the bandwidth is unaffected by the initial compaction conditions of the specimens. However higher the liquid limit of the soil, higher is the equilibrium bandwidth. Tests were also conducted with higher surcharge pressures. As expected the equilibrium bandwidths were reduced with increase of surcharge pressure. Fig.17 shows the relationship.
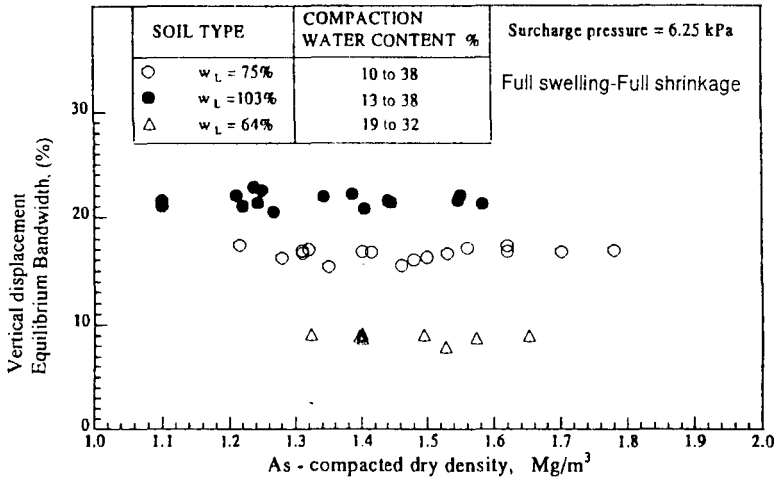
FIGURE 16 : Comparison of Equilibrium Bandwidths for Soils with Different Liquid Limits
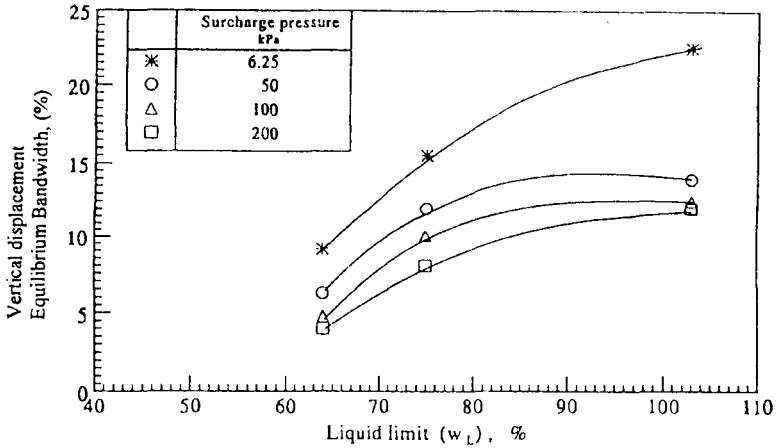
FIGURE 17 : Effect of Liquid Limit and Surcharge Pressure on Equilibrium Bandwidths of Expansive Soils

The equilibrium bandwidth gets established even under full-swelling and partial shrinkage cycles. However, the magnitude of bandwidth is affected by the amount of drying allowed during each shrinkage cycle. Results of Gangadhara (1997) are shown in Fig.18. A bandwidth of 16% under full shrinkage conditions reduces to 4% for partial shrinkage, with water contents at shrunken levels maintained at 20%.
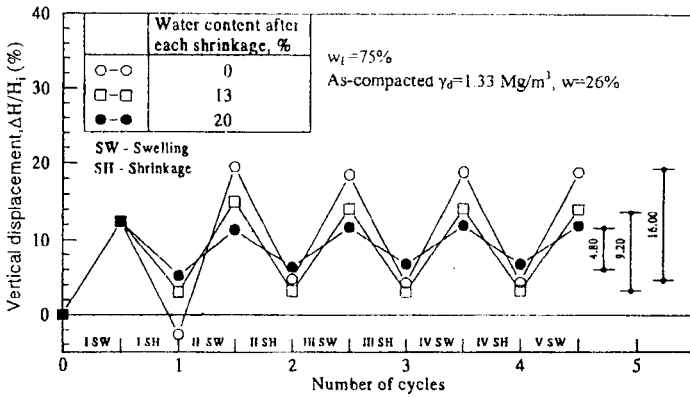
FIGURE 18 : **Full Swelling-Partial Shrinkage Cyclic Experiments with Three Levels of Shrinkage**

To study the effect of sequence of wetting and drying process (i.e., either swell-shrink pattern or shrink-swell pattern) on the equilibrium band width values, experiments were performed by Gangadhara (1997) on two soils (w_L = 75% and 103%) under two surcharge pressures of 6.25 kN/m^2 and 100 kN/m^2. He chose two compaction water contents and two dry densities for each soil. Full swelling and full shrinkage was adopted in each cycle. His results showed that even when the testing was changed to shrink-swell pattern, the equilibrium bandwidth gets established in just about the same number of cycles and the bandwidth is unaffected by the initial placement conditions. Fig.19

FIGURE 19 : **Comparison of Swell-Shrink and Shrink-Swell Bandwidths**
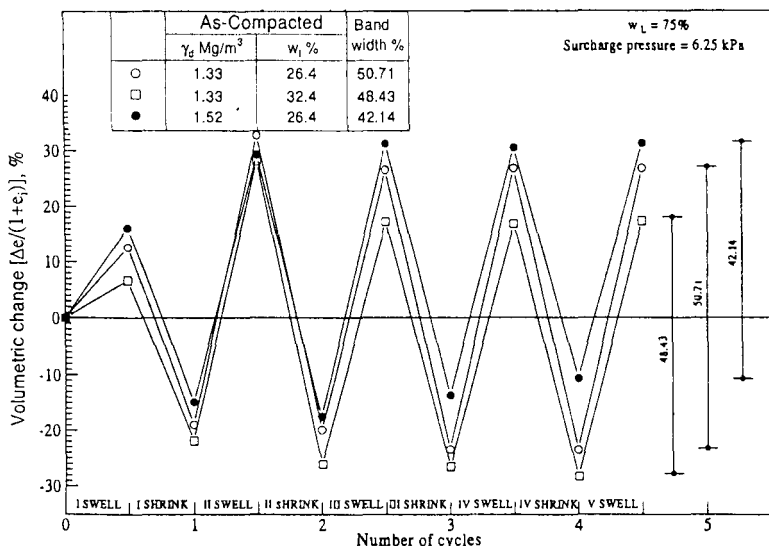
FIGURE 20 : Variation of Volumetric Change with Cycles for Soil
of W_l=75%
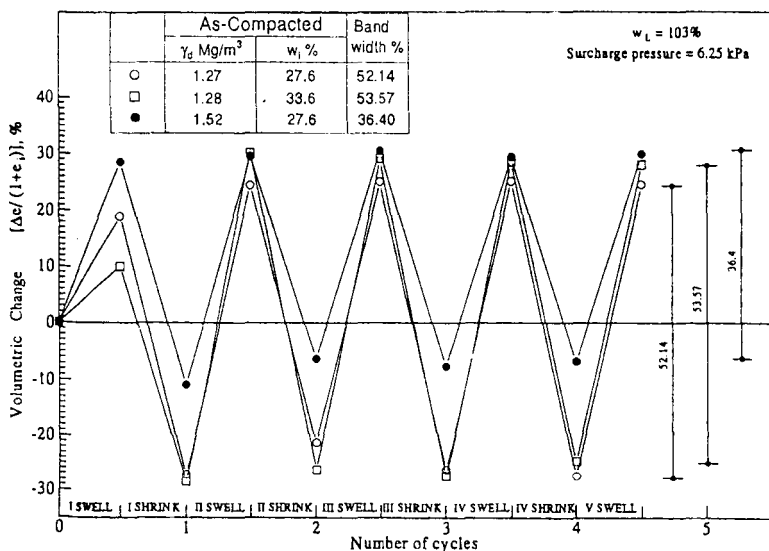
FIGURE 21 : Variation of Volumetric Change with Cycles for Soil
of W_l=103%

shows a typical result. The equilibrium bandwidth remains at about 15% under
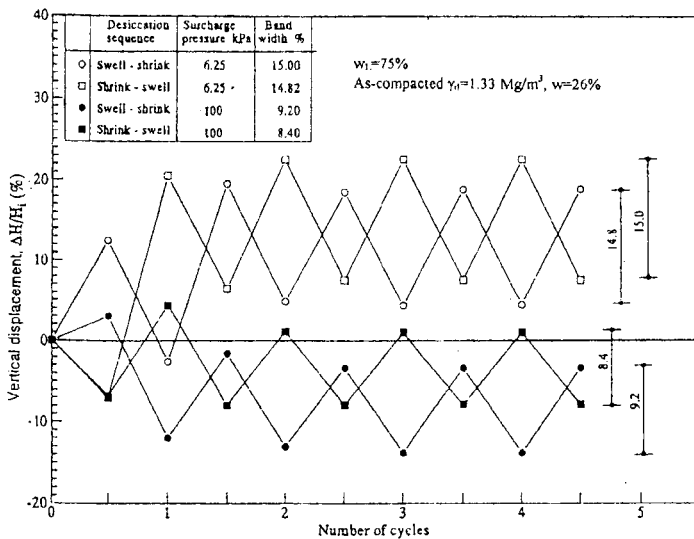6.25 kN/m^2 for both wetting-drying and drying-wetting patterns. Under 100
kN/m^2, the bandwidth value is about 9%.
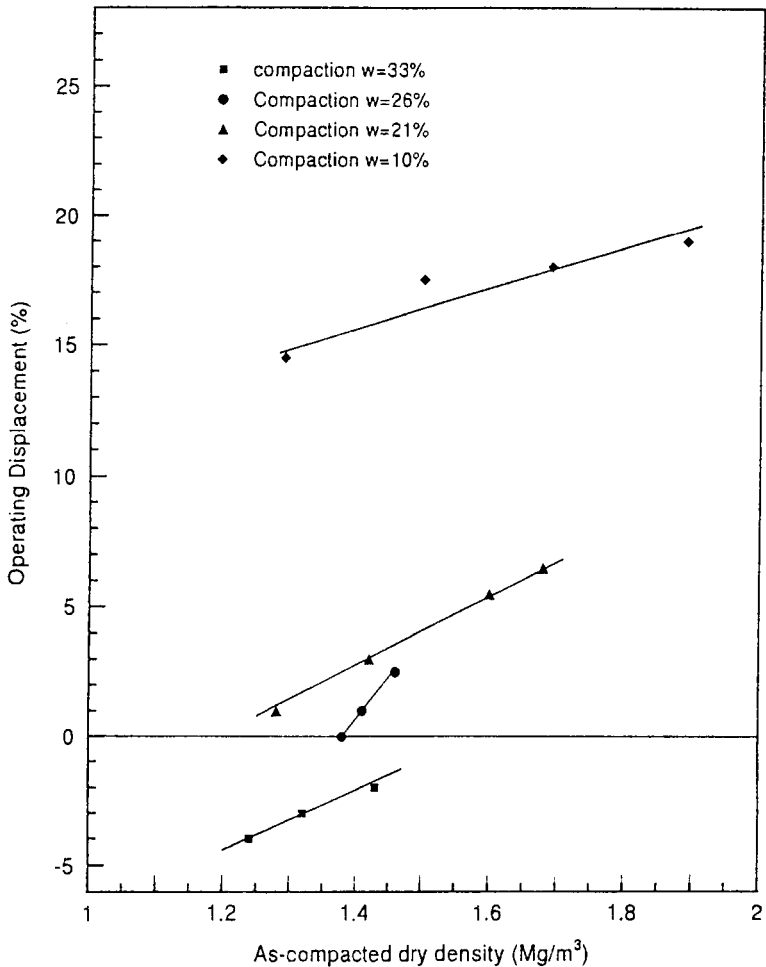
FIGURE 22 : Effect of Initial Conditions on the Operating Displacement for Soil of $W_l = 75\%$

Gangadhara (1997) also analysed the results in terms of volumetric change, $\Delta e/(1+e_i)$, where Δe is the change in void ratio during each swelling or shrinkage cycle and e_i is the initial or as-compacted void ratio of the specimen. Even in this case, a bandwidth exists as can be seen in Figs.20 and 21. However, the uniqueness associated with vertical displacement is not found here, in that the volume change is influenced by both the placement density and water content. The reason can be attributed to the reduction in cross sectional area, which the sample undergoes in each drying cycle. Tests conducted by Gangadhara (1997) have shown that larger the reduction in cross sectional area, larger would be the volumetric swell potential upon wetting. In contrast, the cross
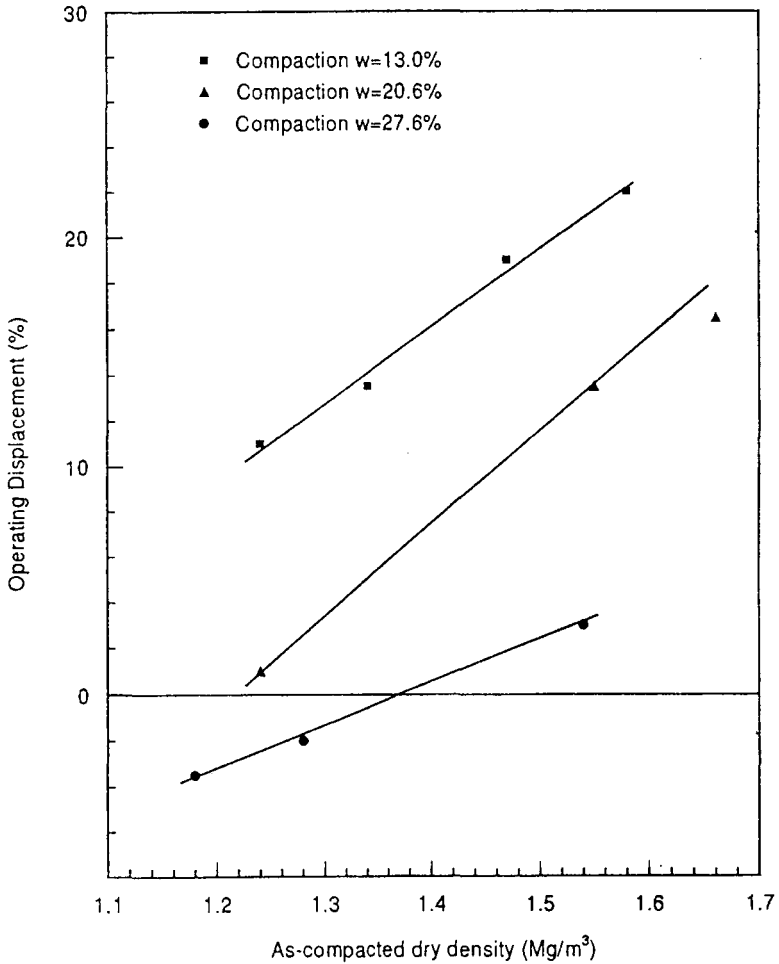
FIGURE 23 : Effect of Initial Conditions on the Operating Displacement for Soil of $W_l = 103\%$

sectional areas of the specimen do not influence the vertical swell potentials.

Operating Displacement

When soil specimen is subjected to wetting and drying, the differences in the magnitudes of vertical displacements in the initial cycles will cause the specimen a permanent change in the operating middle level. The operating displacement could be either positive or negative depending upon the mode of swell–shrink behaviour. Further there is no uniqueness as found for equilibrium bandwidth. The relationship between operating displacement and
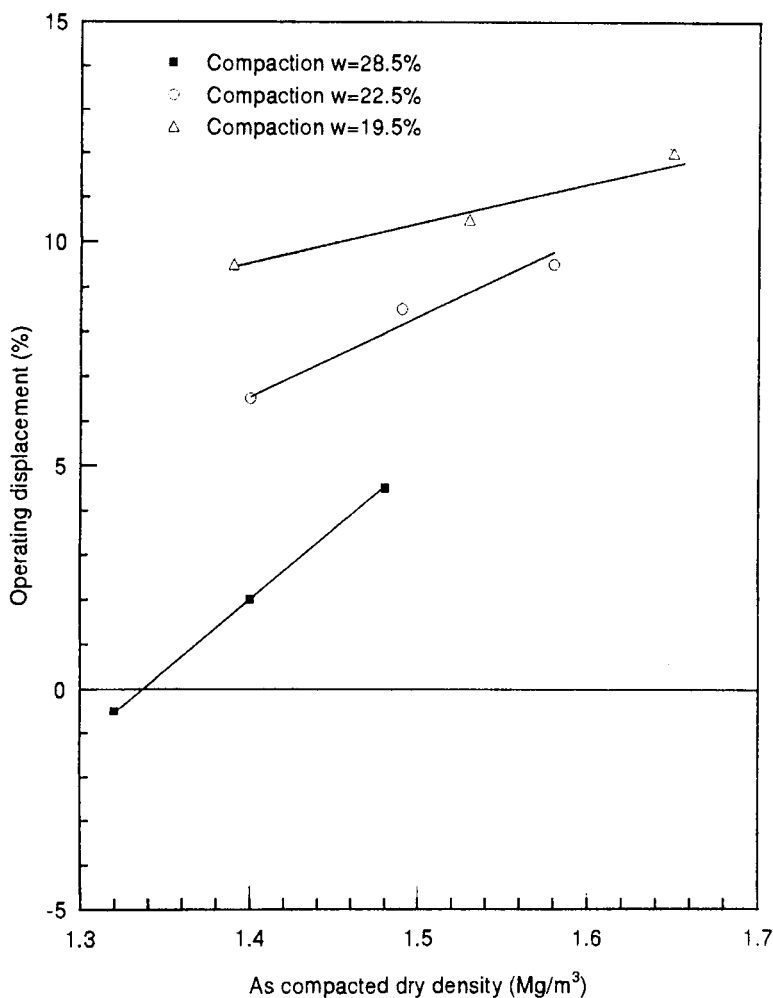
FIGURE 24 : Effect of Initial Conditions on the Operating Displacement for Soil of $W_1 = 64\%$

the initial compaction conditions of the soil are shown in Figs.22, 23 and 24 for the three soils (Gangadhara, 1997). The plots clearly demonstrate a linear relationship between operating displacement and as-compacted dry density. For any particular compaction water content, the operating displacement increases with increase in the as-compacted dry density. The figures also suggest that for high as-compacted dry densities and low water contents, type A/B mode of swell-shrink behaviour would result, for which operating displacement is positive. Similarly, for low as-compacted dry densities and high water content, type D/E mode of swell-shrink behaviour will result for which the operating displacement is negative.

Invariant Swell Potential

What has been observed in the earlier results is that the swelling potentials vary from cycle to cycle till they reach equilibrium level. Most generally, the swelling potential during the second cycle (swelling after first shrinkage) is usually the highest if the specimen is on the dry side of optimum, thereafter the potentials gradually decrease and become steady. The difference in the potential from the first cycle to the last cycle was not insignificant.

FIGURE 25 : Placement Conditions of the Specimens Selected for the Study of Invariant Swell Potential with Cycles (Along 83% S_r Line)

It would be interesting to find if a compaction state exists for which the swell potential remains unaltered with cycles. For this purpose, a search was made (Mahesh Kumar, 1998) at the maximum dry density level of 1.44 Mg/m^3 by changing the water content level. Apart from specimen A3, two more specimens (A2 and A8) were chosen as shown in Fig.25. The tests were conducted with chosen patterns o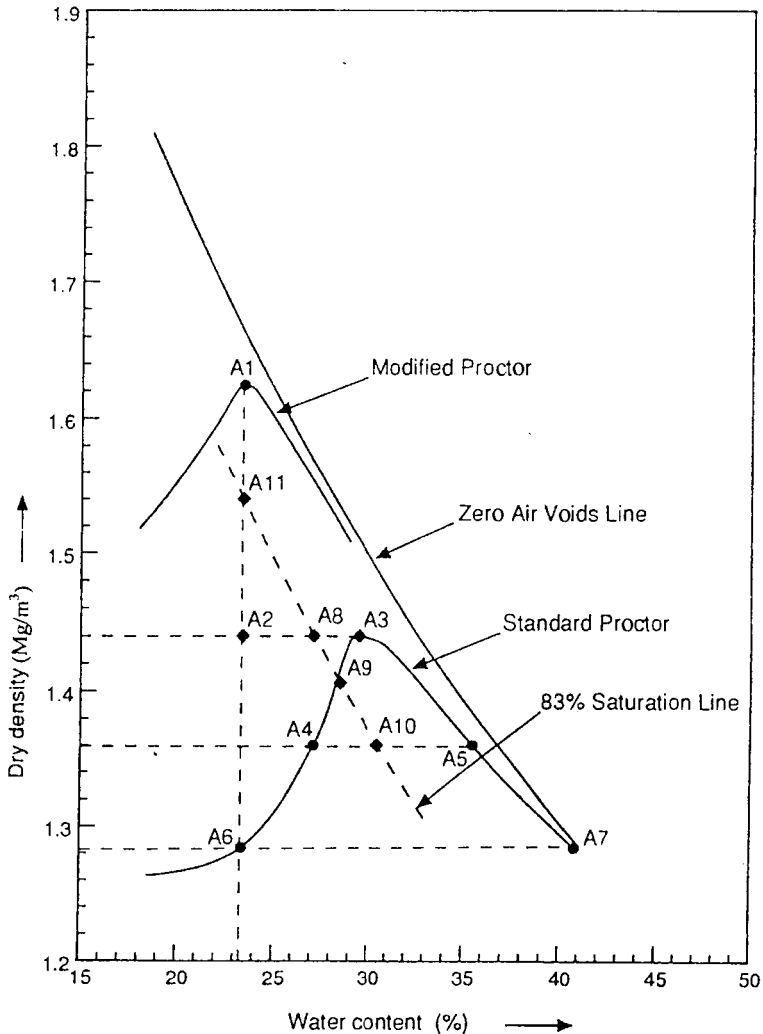f full swelling and 100% shrinkage in each cycle. In other words, the specimens were shrunk back to the initial height in every cycle. For specimen A2 it was not possible to conduct full swelling-100% shrinkage tests, since from the second shrinkage cycle itself, the full shrinkage band was more than the specimen height. Specimen A8 is seen to give the desired result (Fig.26) of the same swelling potential in each of the cycles. The initial degree of saturation corresponding to the specimen A8 is 83%. As a continuation of this search it was felt desirable to check whether the specimens having the degree of saturation of 83% would behave in a similar fashion. So two more specimens were selected, specimens A9 and A10. Specimen A9 is on the standard compaction curve itself. A10 has still lower dry density and higher water content. Very interestingly, both the specimens A9 and A10 showed the consistency of swelling potentials with cycles as seen in Figs.27 and 28. As expected, the magnitude of swelling was the least for specimen A10 on account of its least dry density and highest water content. It is to be observed that all the three specimens A8, A9 and A10 are on the 83% saturation line but have the dry density equal to or less than standard Proctor maximum dry density. To check whether or not this behaviour is observed even for specimen
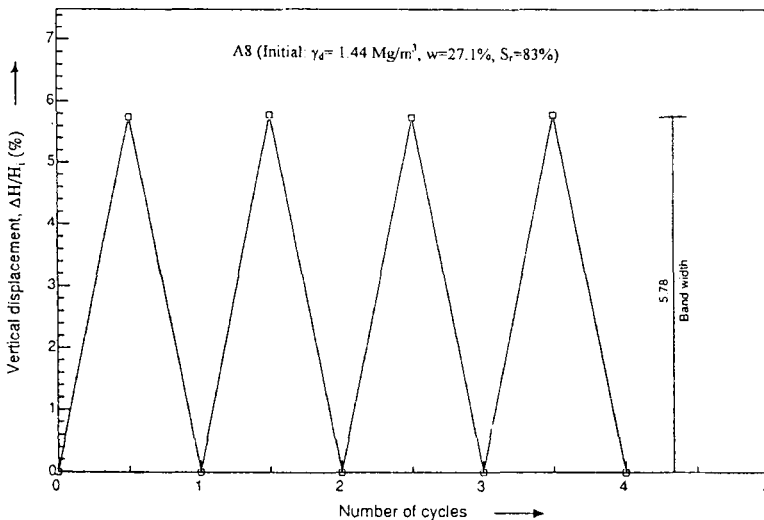
FIGURE 26 : Specimen A8 Showing the Same Swell-Shrink Movements In Each Cycles (Full Swelling - 100% Shrinkage)
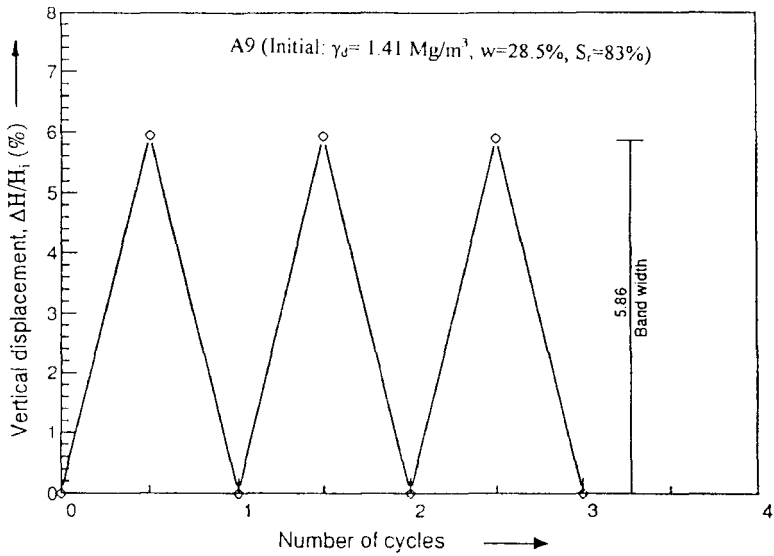
FIGURE 27 : Specimen A9 Showing the Same Swell-Shrink Movements in
Each Cycles (Full Swelling - 100% Shrinkage),
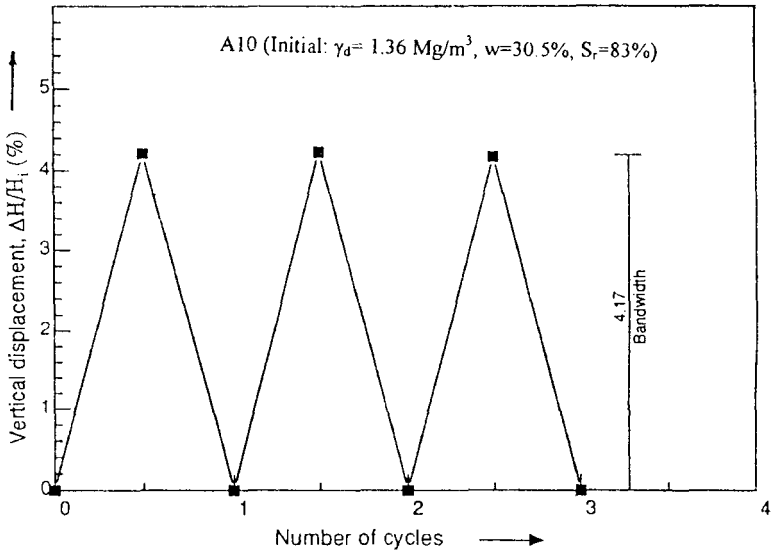
FIGURE 28 : Specimen A10 Showing the Same Swell-Shrink Movements in
Each Cycles (Full Swelling - 100% Shrinkage)
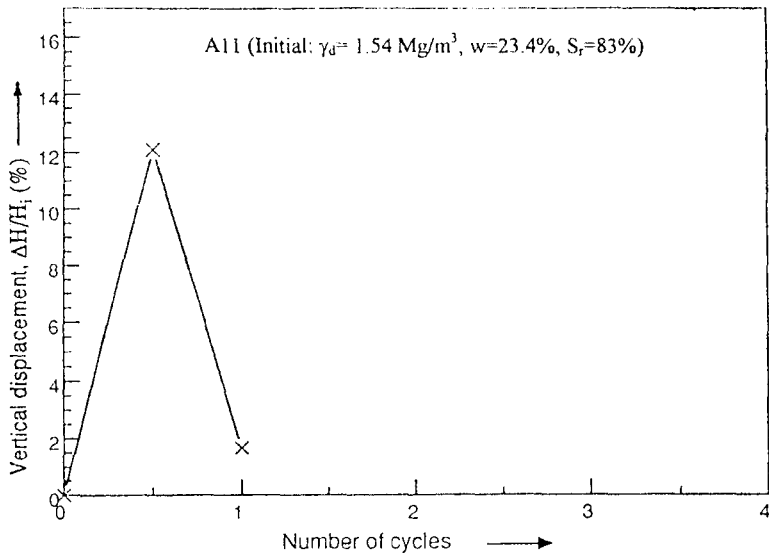
FIGURE 29 : Swell-Shrink Movement of Specimen A11 under Full Swelling - Full Shrinkage Conditions

having dry density higher than the Proctor maximum dry density, one more specimen A11 was chosen corresponding to dry density equal to 1.54 Mg/m^3 and water content 23.4%. Fig.29 shows that this specimen could not be subjected to 100 % shrinkage at all. It therefore appears that for any given soil there will be a set of compaction states for which the cyclic swell potential remains unaltered with cycles of full swelling and 100% shrinkage. For the chosen soil with w_L = 72%, this state correspond to dry density of 1.44 Mg/m^3 or a little lower and degree of saturation of 83%.

Shear Strength Variation

Mahesh Kumar (1998) selected different compacted specimens to study basically how the density and water content vary with each cycle. The time readings associated with specimens A1, A3 and A6 are shown in Figs.30, 31 and 32. It is clear from these figures that the time development curves differ widely until equilibrium state is reached, which in this case happens beyond fifth cycle for A1, sixth cycle for A3 and beyond fifteenth cycle for A6. Once the equilibrium is reached the swell-shrink time curve will repeat itself.

Figures 33 and 34 show the variation of water content at swollen and shrunken states for specimens A3 and A6 respectively. Similarly, Figs.35 and 36 show the variation of dry density at swollen and shrunken levels
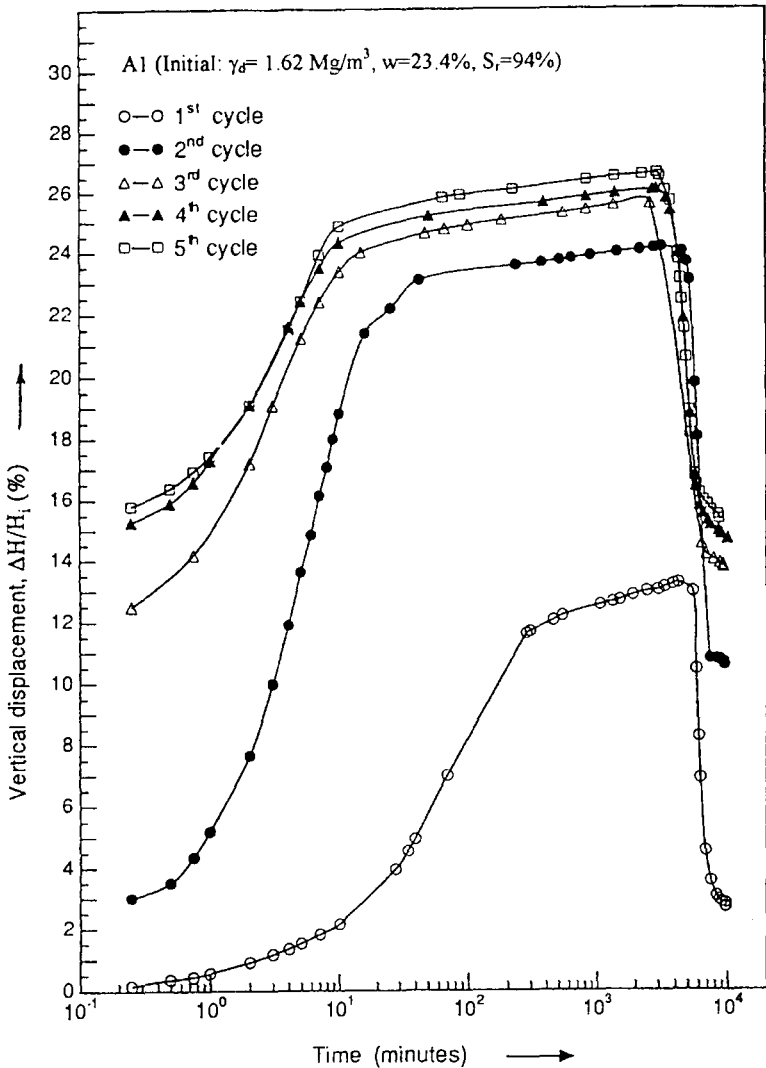
FIGURE 30 : Swell-Shrink-Time Curves for Specimen A1

for A3 and A6. At swollen states in each of the cycles, the degree of saturation was found to be 100%. It is interesting to observe that alternate wetting and drying would induce (for the specimens on the dry side of optimum) an increase in trend of dry density at swollen states till equilibrium is reached. The water content shows the reverse trend. On the contrary, the shrunken states with cycles show a decrease in trend of water content after the first desiccation. Such variations will have practically important bearing on the shear strength of expansive soils with cycles. As it was difficult to conduct shear tests directly on the oedometric samples

A3 (Initial: γ_d= 1.44 Mg/m^3, w=29.5%, S$_r$=90%)

o—o 1st cycle
●—● 2nd cycle
△—△ 3rd cycle
▲—▲ 4^{h} cycle
□—□ 5^{h} cycle
■—■ 6^{h} cycle

Vertical displacement, $\Delta H/H_i$ (%)

Time (minutes)
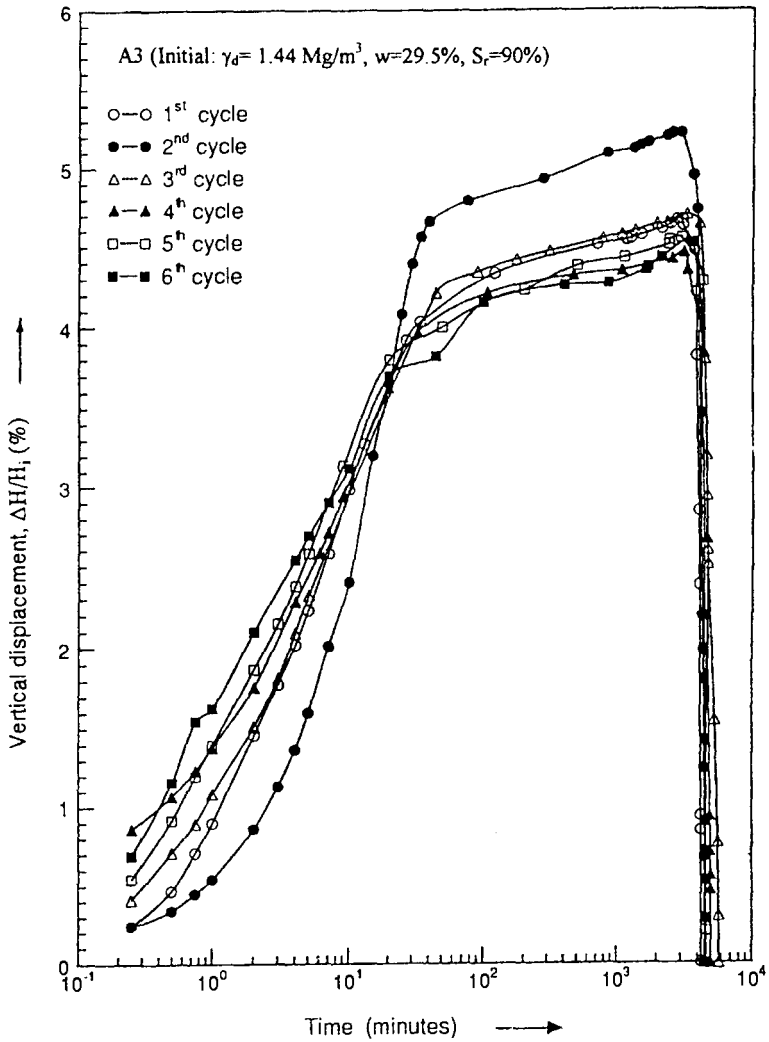
FIGURE 31 : Swell-Shrink-Time Curves for Specimen A3

undergoing swelling and shrinkage, Mahesh Kumar (1998) conducted the same tests on reconstituted soil specimens.

Vane shear tests were conducted by him at the swollen states and triaxial UU tests at shrunken states. Tables 1 and 2 give the dry density and moisture content values at swollen and shrunken states for A3 and A6 samples. The specimens reconstituted to the values of dry density and water content corresponding to swollen states shown in Tables 1 and 2 resulted in vane shear strengths as shown in Figs.37 and 38. It must be mentioned here that the
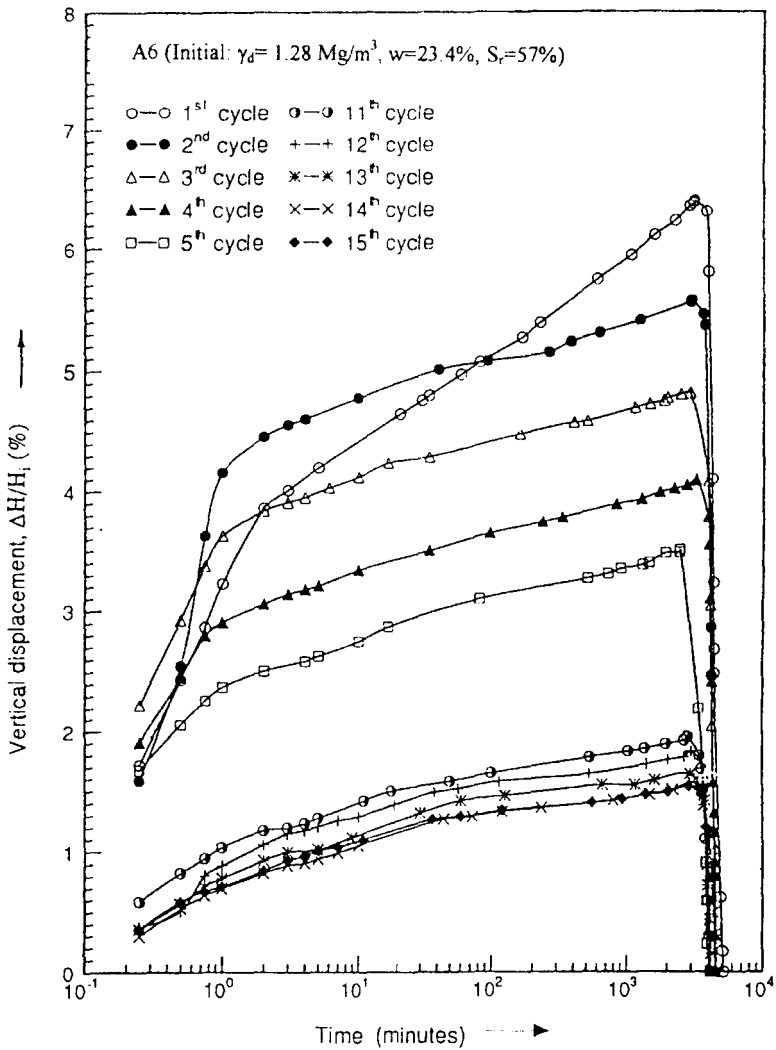
FIGURE 32 : Swell-Shrink-Time Curves for Specimen A6

swollen level water contents are far less than liquid limit water contents, roughly close to 50% value. So, even though the degree of saturation is 100% at swollen level, specimens will still have significant shear strength. Figs.39 and 40 show typical deviator stress-strain responses for the reconstituted shrunken specimens. It can be observed very clearly from the figures that the shear strength varies considerably over the cycles till an equilibrium state is reached. The shear strength parameters c_u and φ_u obtained for all the specimens in each of the cycles of shrinkage are shown in Tables 3 and 4. As expected, the shrunken states will have very high shear strength levels.
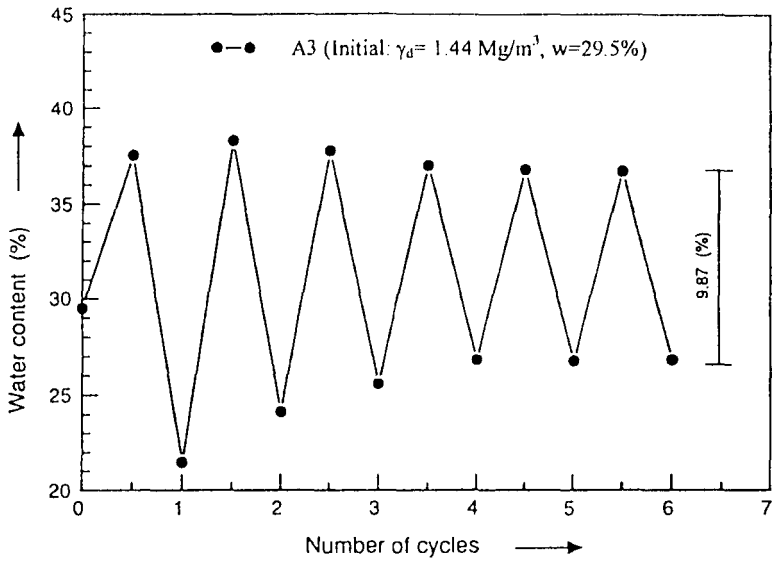
FIGURE 33 : Water Content Variation with Number of Cycles for Specimen A3 (Full Swelling - 100% Shrinkage)
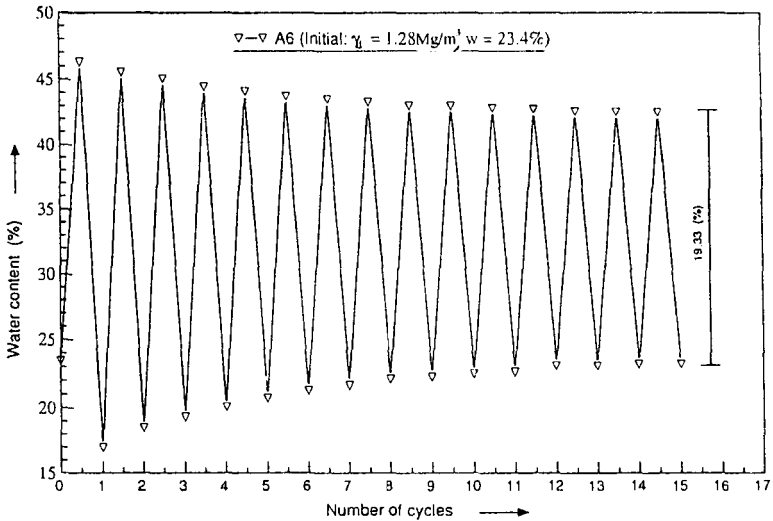
FIGURE 34 : Water Content Variation with Number of Cycles for Specimen A6 (Full Swelling - 100% Shrinkage)
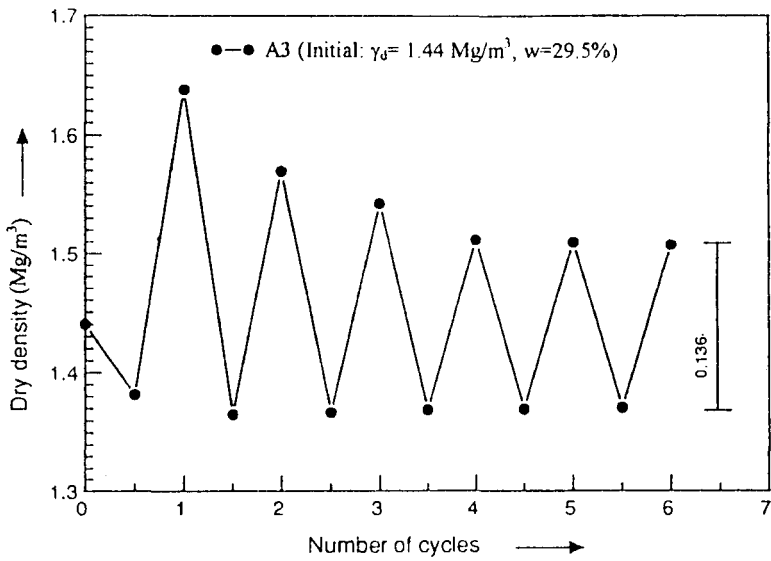
FIGURE 35 : Dry Density Variations with Number of Cycles for Specimen A3 (Full Swelling - 100% Shrinkage)
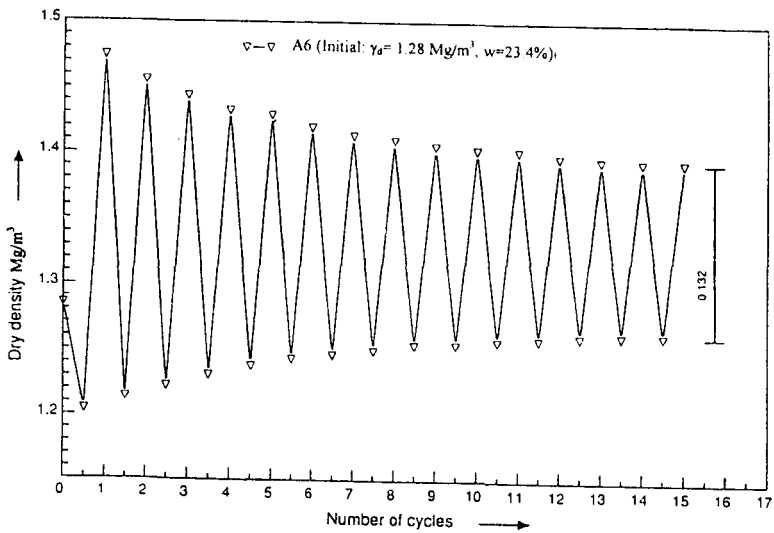
FIGURE 36 : Dry Density Variations with Number of Cycles for Specimen A6 (Full Swelling - 100% Shrinkage)

Table 1 : Swollen and Shrunken State Placement Conditions of Specimen A3

Cycle No.	Dry Density (Mg/m^3) (Swollen state)	Water content (%) (Shrunken state)	Dry Density (Mg/m^3) (Swollen state)	Water content (%) (Shrunken state)
Initial	1.440	29.50	1.440	29.50
1	1.381	37.53	1.638	21.50
2	1.365	38.31	1.569	24.16
3	1.366	37.77	1.542	25.60
4	1.368	37.02	1.511	26.84
5	1.369	36.81	1.509	26.83
6	1.370	36.74	1.507	26.87 .

Table 2 : Swollen and Shrunken State Placement Conditions of Specimen A6

Cycle No.	Dry Density (Mg/m^3) (Swollen state)	Water content (%) (Shrunken state)	Dry Density (Mg/m^3) (Swollen state)	Water content (%) (Shrunken state)
Initial	1.284	23.40	1.284	23.40
1	1.204	46.30	1.474	16.99
2	1.213	45.53	1.456	18.50
3	1.222	45.06	1.444	19.32
4	1.230	44.42	1.432	20.04
5	1.237	44.08	1.429	20.72
6	1.242	43.71	1.420	21.24
7	1.246	43.49	1.413	21.65
8	1.249	43.29	1.410	22.05
9	1.253	43.01	1.406	22.23
10	1.253	42.99	1.403	22.45
11	1.256	42.82	1.402	22.60
12	1.258	42.73	1.397	23.05
13	1.260	42.58	1.395	23.04
14	1.261	42.52	1.394	23.15
15	1.261	42.50	1.394	23.17
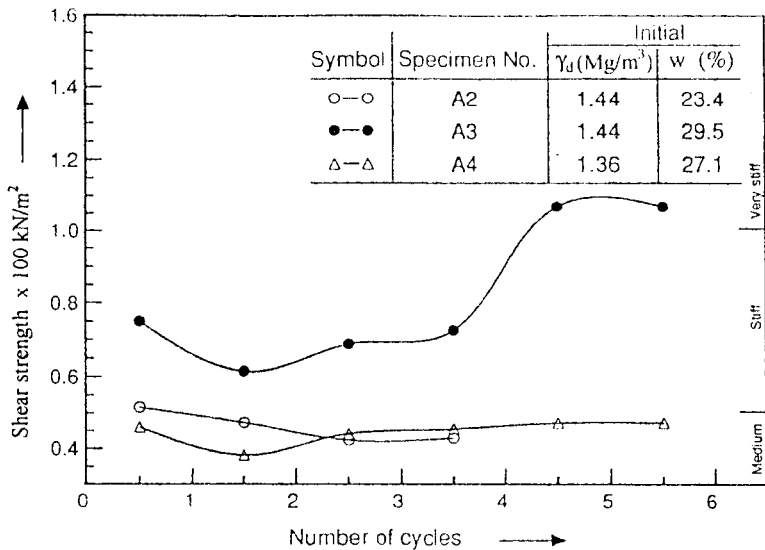
FIGURE 37 : Variation of Vane Shear Strength at Swollen Levels for Specimens A2, A3 and A4
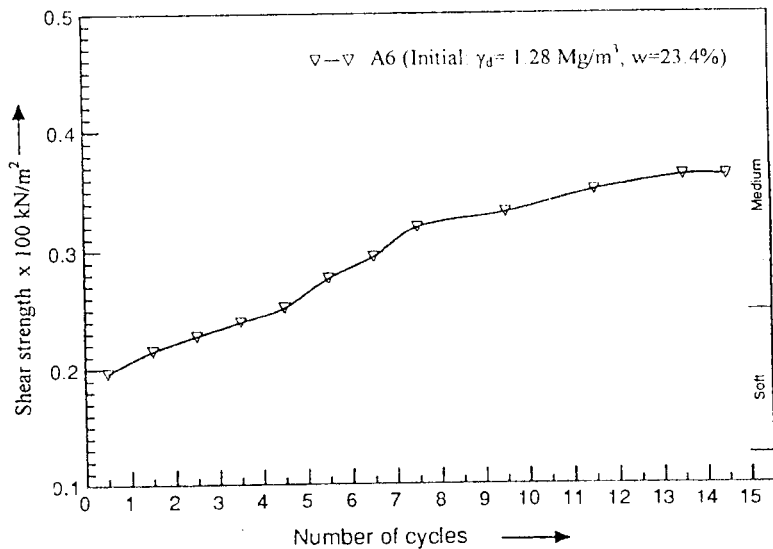
FIGURE 38 : Variation of Vane Shear Strength at Swollen Levels for Specimen A6
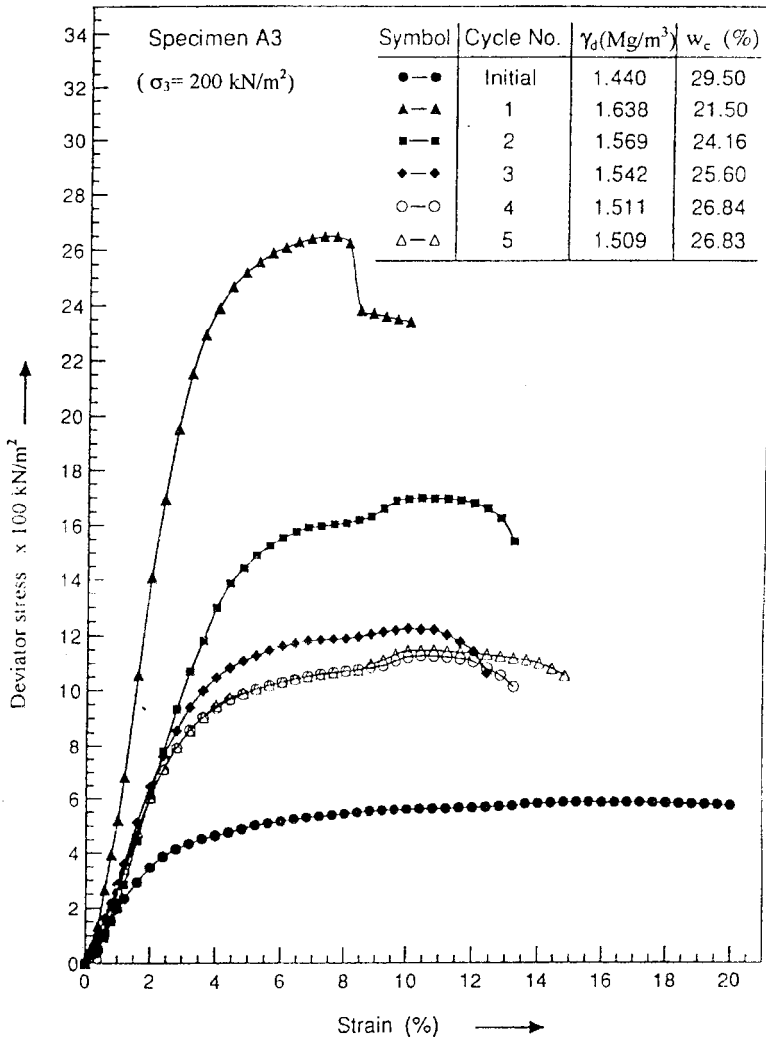
FIGURE 39 : Stress-Strain Curves for Specimen A3 at Shrunken Levels (100% Shrinkage)

Reversibility of Swelling and Shrinkage

The tests have clearly demonstrated that the swelling and shrinkage are not reversible processes during the initial cycles. However, once the equilibrium state is reached and an equilibrium bandwidth of movement is established, the swelling and shrinkage become reversible process. Not only the magnitudes of swelling and shrinkage are equal, but also swell-shrink time paths gets repeated. As mentioned earlier the equilibrium state at which

Symbol	Cycle No.	$\gamma_d(Mg/m^3)$	w_c (%)
●--●	Initial	1.284	23.40
▲—▲	1	1.474	17.00
■—■	2	1.456	18.50
◆--◆	3	1.444	19.32
○—○	4	1.432	20.04
△—△	5	1.429	20.72
◇—◇	6	1.420	21.24
▽—▽	7	1.414	21.65
□—□	9	1.406	22.23
▼--▼	11	1.402	22.60
—	12	1.398	23.05
o—o	15	1.394	23.17
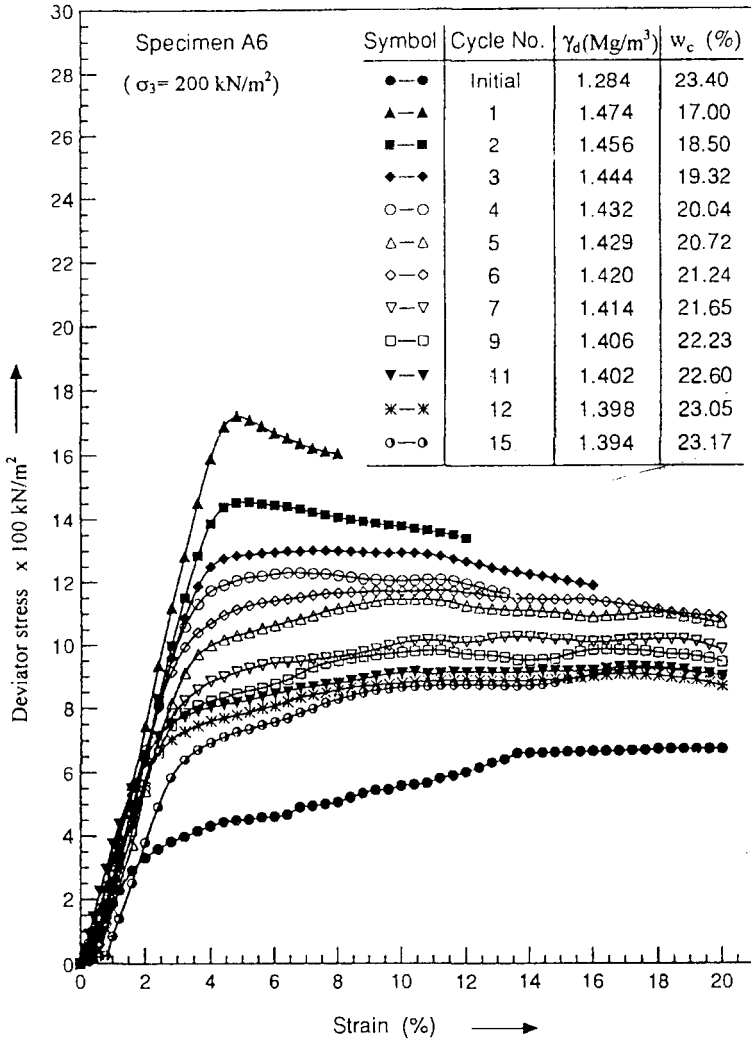
FIGURE 40 : Stress-Strain Curves for Specimen A6 at Shrunken Levels
(100% Shrinkage)

this reversibility is achieved usually gets established in about 5 cycles excepting some extreme cases of very low densities.

Re-establishment of Equilibrium State

Soils above the water table continuously undergo wetting and drying due to seasonal fluctuations of environment. Under a fixed pattern of environment, movements associated with wetting and drying would have reached a steady state. When this steady state is altered, like for example

Table 3 : Shear Strength of Specimen A3 at 100% Shrinkage Levels

Cycle No	Cohesion intercept, c (kN/m^2)	Friction angle, ϕ°
1	960	15.7
2	610	14.0
3	445	14.4
4	435	10.8
5	435	11.5
6	435	11.2
Initial as-compacted	168	14.7

Table 4 : Shear Strength of Specimen A6 at 100% Shrinkage Levels

Cycle No	Cohesion intercept, c (kN/m^2)	Friction angle, ϕ°
1	440	25.5
2	375	25.0
3	350	22.5
4	290	26.5
5	260	26.0
6	240	28.5
7	215	27.0
9	195	27.0
11	190	25.5
12	187	25.0
15	185	25.5
Initial as-compacted	145	15.5

when a structure is built over the soil involving activities, such as excavation, loading etc., the soil-foundation system will again have to reach a level of equilibrium. This usually takes place over a few seasons. When one pattern of environment gives rise to another pattern of environment then also the old equilibrium will have to give rise to new equilibrium. To examine how this will happen and how they affect the equilibrium bandwidth, Subba Rao and Tripathy (1999) conducted experiments by changing the swell-shrink patterns.
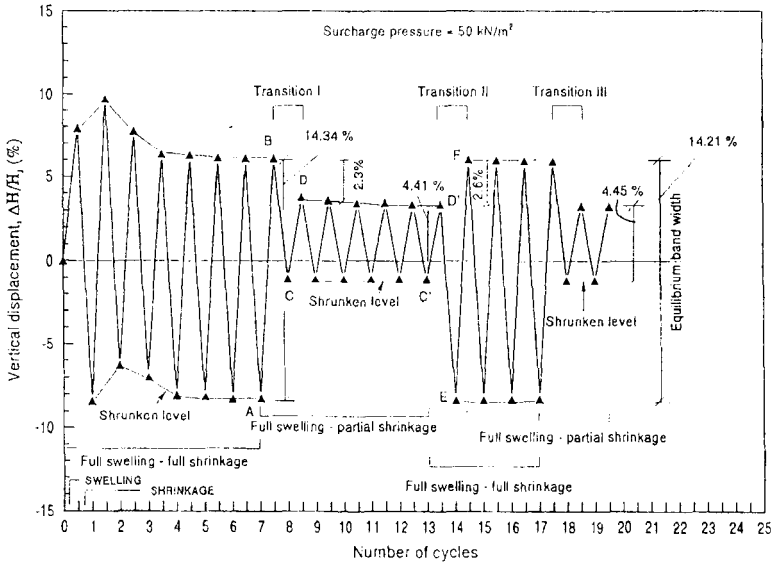
FIGURE 41 : Swell-Shrink Rhythms of Full Shrinkage and
Partial Shrinkage

Figure 41 shows the vertical displacement percentages when full swelling-full shrinkage pattern and full swelling-partial shrinkage pattern occur alternately. It is interesting to observe that there is a particular bandwidth associated with particular swell-shrink pattern and it remains unaltered. In other words, the moment the pattern is restored, the same bandwidth gets established. The soil thus displays memory in terms of band width (refer to 14.34%, 4.41%, 14.21% and 4.45% as marked in Fig.41).

Figure 42 shows the vertical displacement response when one partial shrinkage pattern (50% of the first swollen height) and another partial shrinkage pattern (100% of the swollen height) occur alternately. Here, there is an interesting phenomenon.

As long as the shrinkage level at any equilibrium state does not exceed the past maximum shrinkage level, the phenomenon of restoration of bandwidth occurs (refer to the bandwidth 4.52%, 2.27%, 4.48%, and 2.23% in Fig.42). A new bandwidth gets established if equilibrium shrinkage level exceeds the maximum past shrinkage level (refer to bandwidth percentage marked as 3.26%, 4.52% in Fig.42). Another interesting observation, which could be made in both Figs.41 and 42, is about the presence or absence of fatigue phenomenon. No fatigue phenomenon is observed when the patterns have shrunken levels that were less than or equal to the maximum past shrunken level of an earlier pattern. Only when shrunken level exceeds the
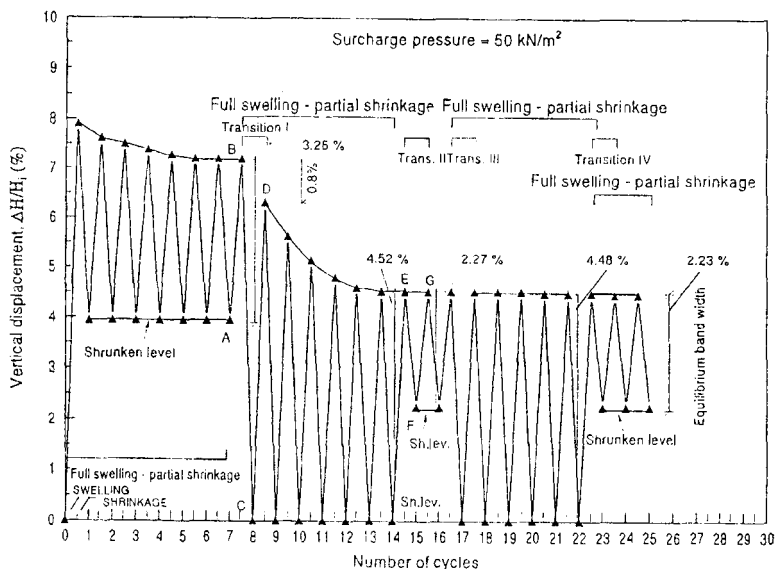
FIGURE 42 : Swell-Shrink Rhythms Involving Partial Shrinkages

maximum past shrunken level, the fatigue phenomenon sets in and it takes a few cycles before equilibrium state is reached. When freshly compacted soil undergoes cyclic movements, fatigue phenomenon obviously is observed (refer up to B in both Figs.41 and 42 and D to E in Fig.42). It follows therefore that the shrunken level (present and past) is the controlling factor in defining qualitatively the particle rearrangement.

Shrinkage Crack Patterns

Photographs of the shrunken specimens were taken by Satyadas (1982) at the end of the tests from the top and from the sides to view clearly an idea of generation and distribution of cracks in the specimens. It is generally known that, when the soil is subjected to repeated cycles of wetting and drying, randomness of particle will increase with increase of cycles. Also, as cycles increase, the particle aggregations and consequently the stiffness will increase (Allam, 1977). It is also known that, the effect of temperature on the sample is to increase randomness of the particles and hence the increase of particle aggregation. It thus follows that one can expect more number of cracks and greater particle aggregation both with the increase of cycles and with the increase of shrinkage temperatures.

Plates 1, 2, 3, and 4 refer to crack patterns seen on specimens with varying surcharges 50 kN/m² to 600 kN/m² and also with different kinds of shrinkage, number of cycles being the same. It is seen that at lower surcharge

Side View

Top View

Plate 1 : 4th Cycle, Shrunken Specimen, Shrunk at 50°C with Surcharge of 50 kN/M^2
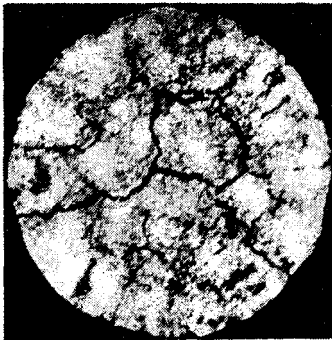
Side View

Top View

Plate 2 : 4th Cycle, Shrunken Specimen, Shrunk at 50°C with Surcharge of 400 kN/M^2
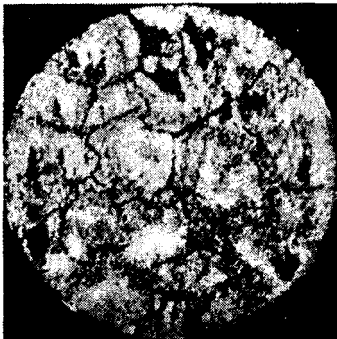
Side View

Top View

Plate 3 : 4th Cycle, Shrunken Specimen, Shrunk at 50°C with Surcharge of 600 kN/M^2

Top View

Side View

Plate 4 : 4th Cycle, Shrunken Specimen, Shrunk at Room Temperature (Average 26°C) with Surcharge of 600 kN/M²

Top View

Side View

Plate 5 : 4th Cycle, Shrunken Specimen, Shrunk at Room Temperature (Average 26°C) with Surcharge of 200 kN/M²

Top View

Side View

Plate 6 : 4th Cycle, Shrunken Specimen, Shrunk at Room Temperature (Average 26°C) with Surcharge of 400 kN/M²

pressures, number of cracks are more and narrower than at higher surcharge pressures. Also at higher surcharge pressures, cracks seem to originate at the center, extending towards the sides. At lower surcharge pressures, origination of crack is from the sides extending towards the center. This can be clearly seen from the side views of the samples. Plates 5 and 6 show the photographs when the specimens under different surcharges were shrunk at room temperature. Comparing Plates 2 and 6 with Plates 3 and 4, the specimens have the same surcharges and have undergone same number of swell-shrink cycles, but the methods of shrinking are different. Plates 2 and 3 refer to specimen shrunk at elevated temperature of 50°C, thus inducing greater rate of shrinkage (total shrinkage taking place in about 8 days).

Plates 4 and 6 refer to specimens shrunk at room temperature (average of 25°C) at a slower rate (total shrinkage taking place in about 45 days). Specimens, which are shrunk at room temperature at a slower rate, show a fewer number of cracks, the distribution being random, cracks are however quite wide. This is probably due to the ease with which already existing cracks would get widened rather than to develop new cracks, since the available temperature gradients are smaller. The specimen shrunk at faster rate using higher temperature of 50°C (Plates 2 and 3) show that the number of cracks are more, but smaller in width. The cracks are distributed uniformly throughout the specimen.

Scanning Electron Micrographic Studies

Tripathy (1999) has done Scanning Electron Micrographic studies and some SEM's are shown in Plates 7 to 13. Initial state of the specimens at start of full swelling-full shrinkage cycles under 50 kN/m^2 surcharge corresponds to Proctor optimum conditions (Plate 7). All the plates show the side views. Plates 8, 10 and 12 show SEM's at the swollen levels of first, second and third cycles. All the swollen level photographs show the particle assemblage in interweaving bunch formation (Collins and McGown, 1974) with intra-assemblage and inter-assemblage pores. All the three show qualitatively similar pictures. Plates 9, 11 and 13 show SEM's at the shrunken levels of first, second and fifteenth cycles. The development of particle aggregations can be clearly seen at the shrunken states. More oriented particle arrangements existing at first shrunken level have given rise to dense matrix formations in the subsequent shrinkage levels.

Behaviour of Shrunken Specimens at Equilibrium State

Earlier results reported herein deal with the behaviour of compacted soil upto the equilibrium state. How the specimen in shrunken state, which has a history of atleast four cycles of wetting and drying behaved when wetted, will now be discussed.
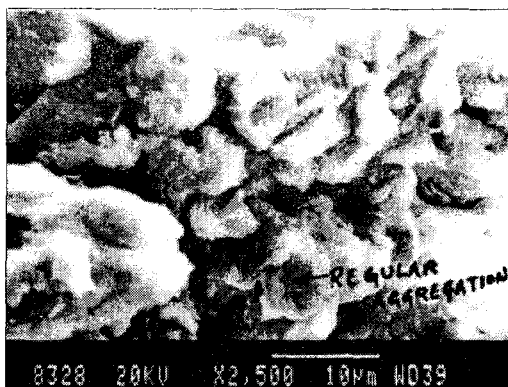
Plate 7 : Compacted at Standard Proctor Optimum Conditions
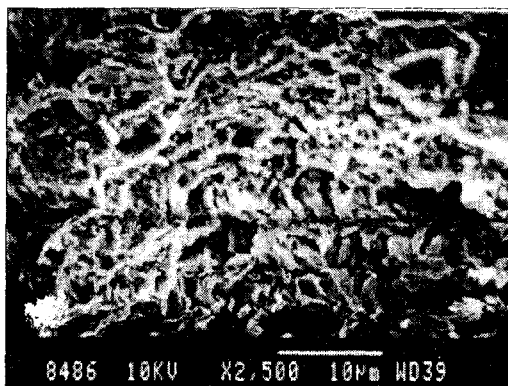
Plate 8 : Swollen Specimen, First Cycle
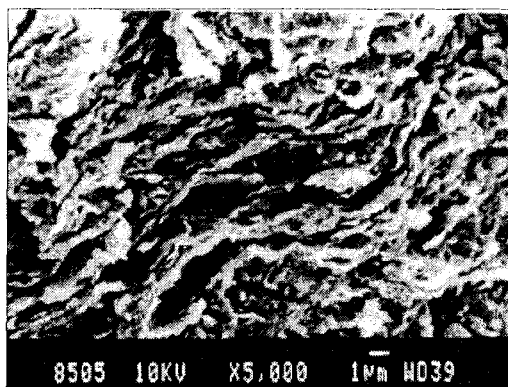
Plate 9 : Shrunken Specimen, First Cycle
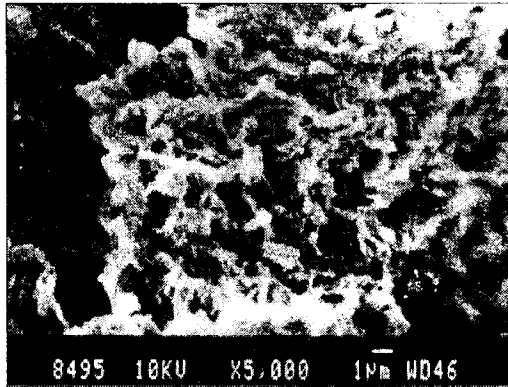
Plate 10 : Swollen Specimen, Second Cycle
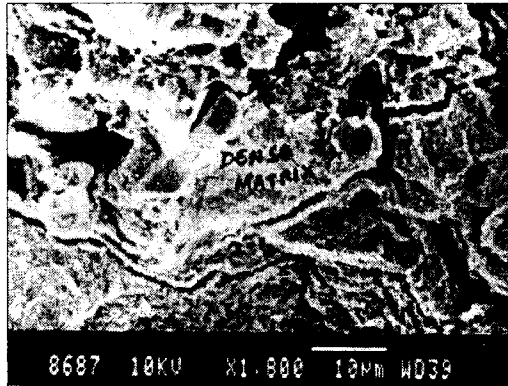
Plate 11 : Shrunken Specimen, Second Cycle
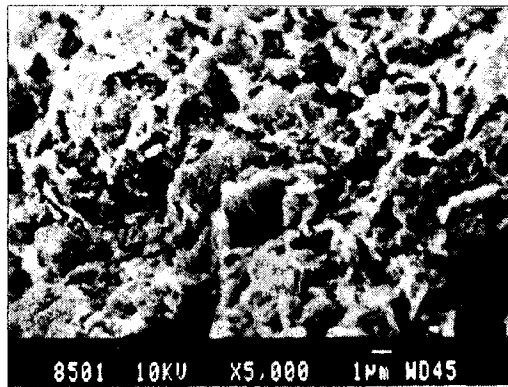
Plate 12 : Swollen Specimen, Third Cycle
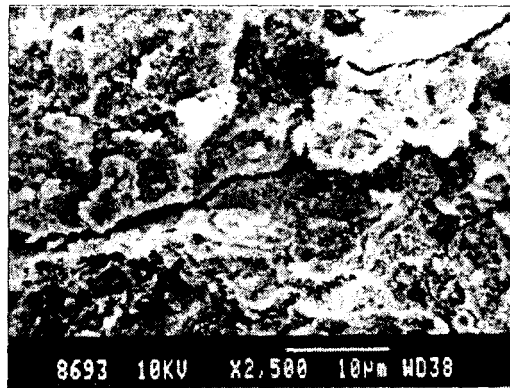
Plate 13 : Shrunken Specimen, Fifteenth Cycle

Studies were conducted by Subba Rao et al. (2000) on expansive soils of liquid limit 75%, statically compacted to different initial water content and densities. To facilitate presentation, the shrunken specimens at the end of four cycles herein are called desiccated specimens. The desiccated specimens were allowed to swell with measurements of both vertical and volumetric swell potentials. The dried specimens expanded both in the lateral and vertical directions on wetting. As-compacted specimen expanded only in the vertical direction in the first wetting. Consequently the vertical swell potential, same as vertical displacement (%) of an as-compacted specimen equalled its volumetric swell potential. The vertical swell potential of a desiccated specimen was calculated as $\Delta H/H_{shrunken}$, where ΔH is the increase in thickness of a desiccated specimen on wetting and $H_{shrunken}$ is the thickness of the desiccated specimen prior to wetting. Vertical swell potential is the same as vertical displacement percentage mentioned earlier in this paper in which H_i equal to the thickness of desiccated specimen prior to wetting.

Volumetric swell potential of desiccated specimen was calculated as $\Delta e/(1+e_{shrunken})$, where Δe is the increase in void ratio of desiccated specimen on wetting and $e_{shrunken}$ is the void ratio of the same specimen prior to wetting. Fig.43 shows a typical plot of swell potential versus pre-inundation dry density. In the same plot are also shown the swell potentials of as compacted specimens. In this figure, point A represents the vertical or volumetric swell potential of as-compacted specimen and points A' and A" represent vertical and volumetric swell potentials of same specimens in the desiccated states. The explanation holds good for points BB'B", CC'C", DD'D". It is interesting to note the dry densities of all desiccated specimens vary with in a narrow range. The water contents of all the desiccated specimens were also nearly constant and ranged between two and three percent. As seen in Fig.43, the volumetric swell potentials of the as-compacted
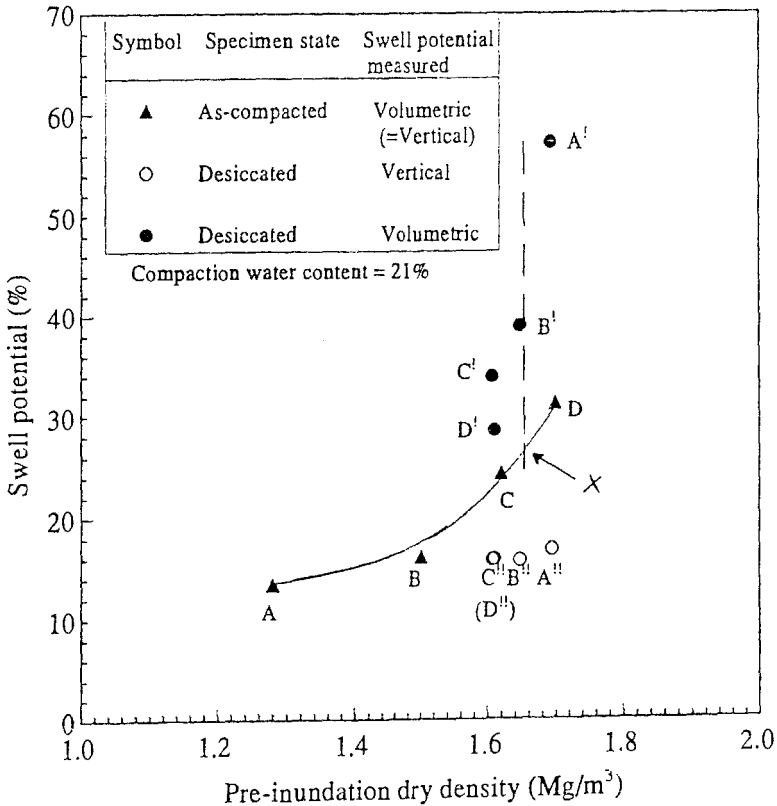
FIGURE 43 : Pre-Inundation Dry Density-Swell Potential Relations for as-Compacted and Desiccated Specimens

specimen expectedly increase with dry density. The desiccated specimens however show marked variations in their volumetric swell potentials despite possessing near similar dry densities and moisture contents prior to inundation, owing to the differences in their lateral swell magnitudes.

Figure 44 plots swell potential versus percent reduction in cross sectional area for desiccated specimens belonging to various compaction water content series. The percent reduction in cross sectional area of a desiccated specimen is defined as the ratio $(A_o - A_d)/A_o \times 100$, where A_o is the cross sectional area of the as-compacted specimen and A_d is the cross sectional area of the same specimen in desiccated condition. The plots of Fig.44 illustrate that irrespective of its compaction water content, a desiccated specimen that has experienced a greater reduction in cross sectional area exhibits a larger volumetric swell potential. The desiccated specimens of all the four-compaction water content series however exhibit near identical vertical swell potentials. The trend of
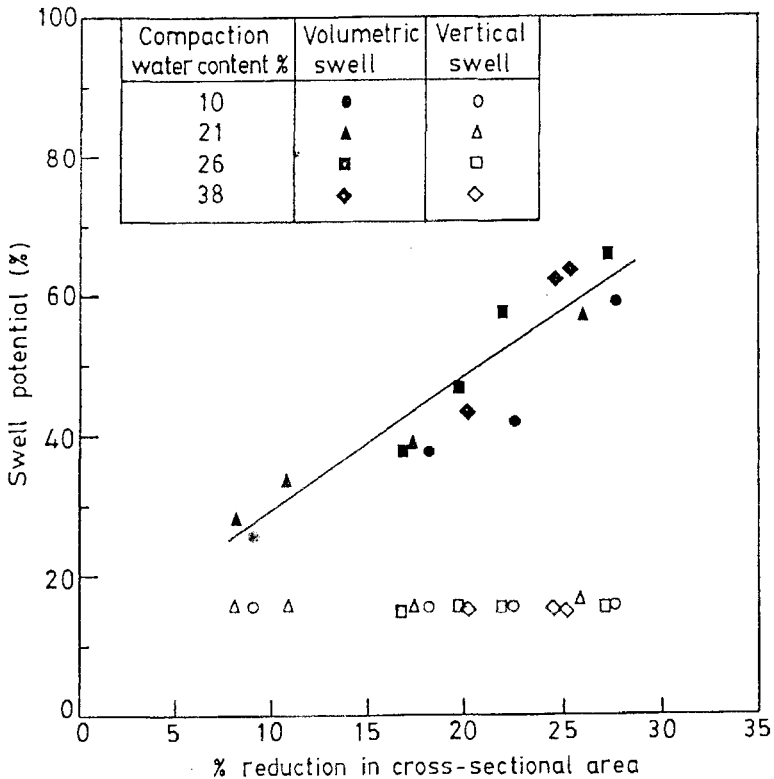
FIGURE 44 : Correlation Between Percent Reduction in Cross-Sectional Area
and Swell Potential of Desiccated Specimens

results in Fig.44 implies that the swelling in the lateral direction is
preferred to swelling in the vertical direction.

Figure 45 plots the relationship between swell potentials of the
desiccated specimens and their $\Delta e_{shrinkage}$ values to different water content
series. The $\Delta e_{shrinkage}$ values in Fig.45 represent the difference between void
ratio of an as-compacted specimen and its desiccated counterpart. A positive
$\Delta e_{shrinkage}$ value indicates that an as-compacted specimen experiences an
increase in void ratio from cyclic wetting-drying effects. The plot in Fig.45
reveals that the $\Delta e_{shrinkage}$ value becomes less positive in magnitude with
reduction in initial void ratio. It emerges from this figure that, irrespective of
the compaction water content, specimens that experience a larger reduction in
void ratio from 4 cycles of wetting and drying also exhibit a larger volumetric
swell potential in the desiccated condition.

The fairly linear relationship in Fig.46 suggests that the volumetric swell
potentials of the desiccated specimens are independent of their compaction

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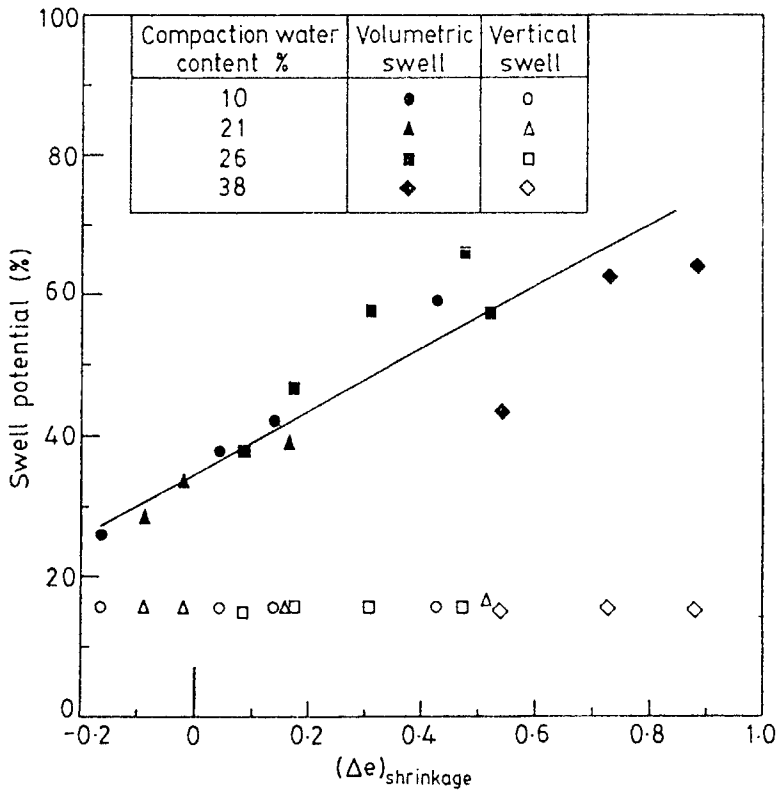
FIGURE 45 : Plot of $\Delta E_{shrinkage}$ vs. Swell Potential of Desiccated Specimens

water content, but are strongly influenced by their initial void ratio. The vertical swell potentials of the desiccated specimens are independent of their compaction water content as well as their initial void ratio. This conclusion has already been drawn in connection with equilibrium bandwidth.

Behaviour of Cushioned Expansive Soils

Of the several alternatives for absorbing the swelling potential of expansive soils, providing a cushion is one popular method adopted in India. Different cushion materials have been used in practice. They are (i) sand, (ii) sand and boulder, (iii) cohesive non-swelling soil (CNS), (iv) lime-stabilised soil, (v) cement-stabilised soil, etc. Thicker the cushion, better will be its efficiency in protecting the overlying foundation from the expansive nature of the soil. Studies on sand cushion made by Satyanarayana (1973) and Moussa et al. (1985) bring out the influence of sand gradation and placement condition on its efficiency. However, the use of sand cushion met with limited success only when the expansive soil shows low to moderate swelling
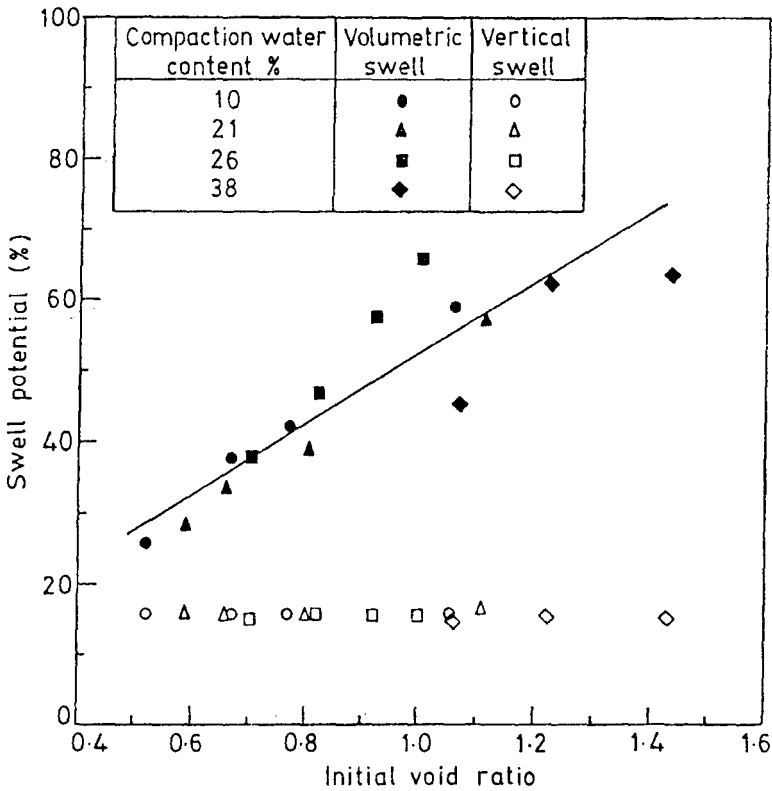
FIGURE 46 : Correlation Between Initial Void Ratio and Swell Potentials of Desiccated Specimens

characteristectics. The reason for this has been thought of as due to the non-cohesiveness of the cushion. This view further got strengthened with the research of Katti and co workers (1967, 1979) which resulted in the development of cohesive non-swelling (CNS) soil as a suitable cushion material. Their findings were all based on first swelling observations. Their results show the cohesion of the CNS layer and its thickness are the governing criteria in counteracting the swelling and swelling pressure. The placement condition of the cushion corresponds to proctor optimum conditions. The specifications as to what constitutes the CNS material, placement conditions and the thickness to be provided have been developed by Katti et al. (1979) for the CNS material.

It was necessary to examine how rigorous is the specifications for CNS soil as suggested by Katti et al. and also approved by Bureau of Indian Standards, because in practice, the locally available reddish brown soil, called murrum is usually taken to be the CNS soil. Therefore Subba Rao et al. (1994) studied the expansive soil with different red earth compositions, one

Table 5 : Physical Properties of Soils

Properties	BC soil	CNS	CNS (NS1)	CNS (NS2)
Grain size analysis:				
Clay(%)	20.0	19.0	38.0	11.0
Sand (%)	67.0	36.0	27.0	19.0
Gravel (%)	13.0	37.0	33.0	55.0
Silt (%)	-	8.0	2.0	15.0
Consistency limits:				
w_L (%)	88.0	37.0	49.0	28.0
w_p (%)	42.0	21.0	24.0	16.0
PI (%)	46.0	16.0	25.0	12.0
w (%)	9.0	18.0	15.0	20.0
Sp. Gravity	2.67	2.72	2.69	2.74
Proctor Compaction Characteristics:				
OMC (%)	36.00	15.70	22.00	12.00
MDD (kN/m³)	12.70	17.13	16.09	19.52
Shear strength of samples compacted to Standard Proctor				
UCC (kN/m²)	-	217.78	201.11	124.59
c_u (kN/m²)	-	74.56	59.84	34.34
ϕ_u (deg.)	-	8.00	9.00	15.00

conforming to the specifications and other two not conforming to the specifications. They were accordingly designated as CNS, CNS (NS1) and CNS (NS2). Table 5 gives the salient details of these materials together with that of black cotton soil (BC). Results of tests conducted show the behaviour in the first swelling. BC soil and any CNS soil used in BC + CNS system were compacted to the respective proctor dry densities, while BC soil was at hygroscopic water contents, CNS, CNS (NS1), CNS (NS2) were compacted at their respective optimum moisture contents. The results clearly demonstrated that the specifications for CNS soil are not so rigorous. In fact, soil with higher clay content CNS (NS1) behaved better than CNS itself. The soil with higher sand content, CNS (NS2) was less effective.

The swell shrink behaviour of different CNS soils under a nominal surcharge during full swelling-full shrinkage is shown in Fig.47. The equilibrium movement is reached just after two cycles for all the soils. The
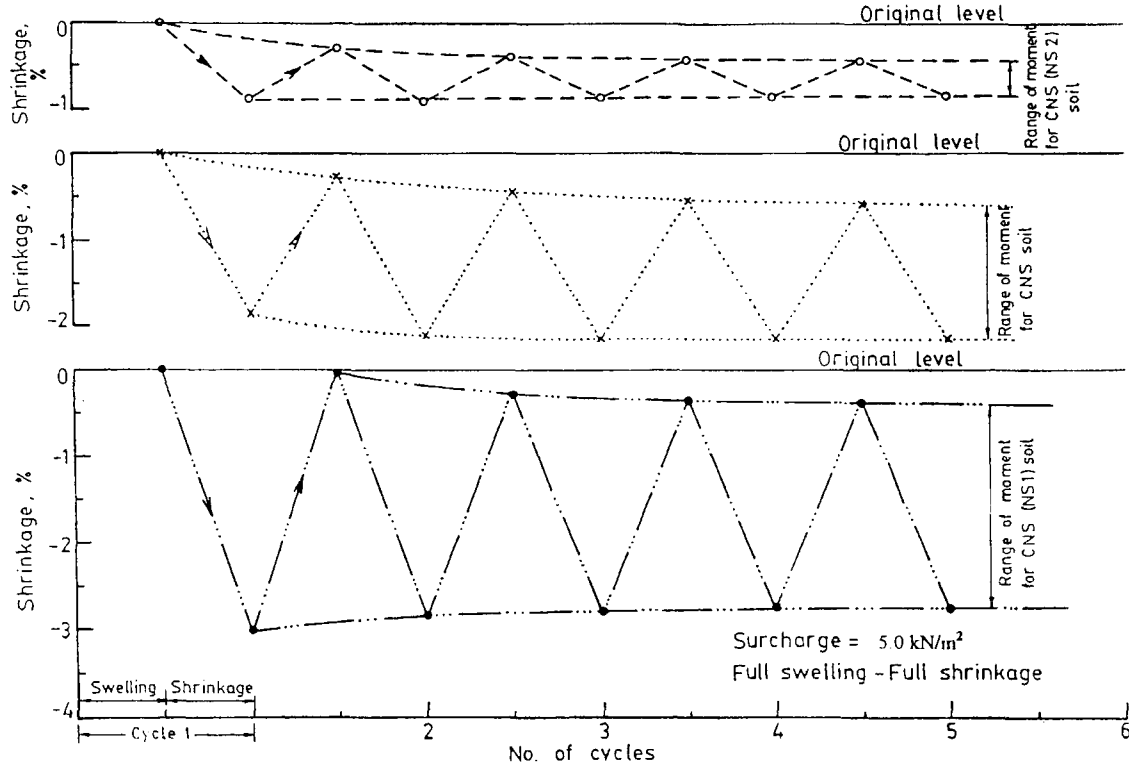
FIGURE 47 : Cyclic Behaviour of Different CNS Soils

	γ_d, gm/cc	w, %
BC Soil	1·295	10·5
CNS (NS2) soil	1·990	12·0
CNS Soil	1·746	15·7
CNS (NS 1) soil	1·640	22·0

Surcharge = 50 kN/m²
Full swelling – Partial shrinkage
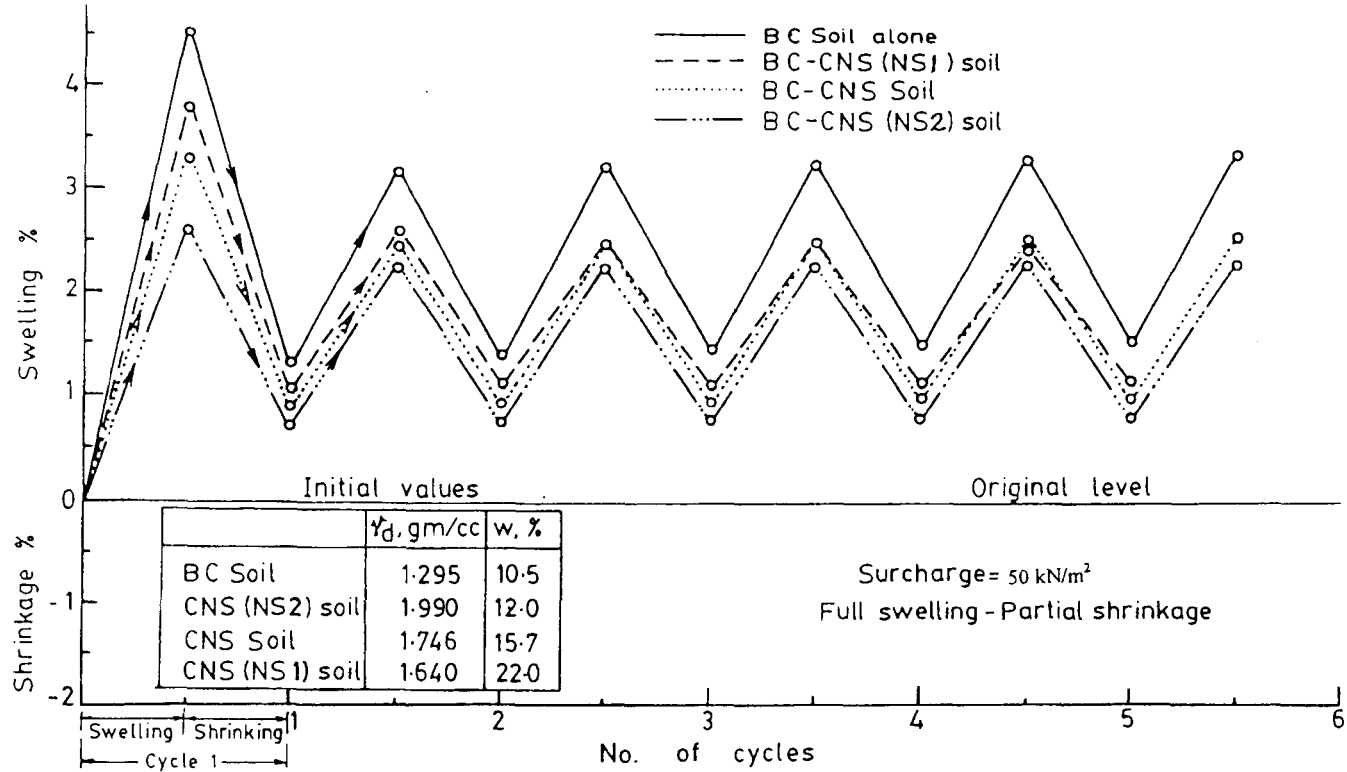
FIGURE 48 : Cyclic Swell-Shrink Behaviour of BC Soil and BC-CNS Soils

equilibrium band widths for CNS (NS1), CNS and CNS (NS2) are 2.35%, 1.65% and 0.4% respectively. It is interesting to observe that the CNS materials though do not swell in the first cycle, but do shrink in the first shrink cycle and then show both swelling and shrinkage behaviour in subsequent cycles. If one were to consider only swelling potential in first cycle, then it is zero for all the three soils. But in long run, they do show shrink-swell behaviour. Since CNS (NS1) has maximum clay content, expectedly its equilibrium bandwidth is maximum.

Subba Rao et al. (1995) studied the swell-shrink behaviour of BC + CNS systems. In one series, cyclic tests with full swelling-full shrinkage were conducted. In another series, cyclic tests with full swelling-partial shrinkage were conducted. In the latter, shrinkage level was kept at 75% of first swollen level. The experiments were conducted on samples prepared in consolidation rings of 76mm diameter and 50mm height. BC soil and CNS soil used in the BC+CNS system were compacted to their respective Proctor dry densities. While BC soil was compacted to a dry density of 12.95 KN/m^3 at hygroscopic water content of 10.5%, the cushions were compacted at their respective optimum water contents. The thickness ratio of BC soil: cushion was 2 : 1. The typical cyclic behaviour of BC + CNS systems under a surcharge of 50 kN/m^2 is as shown in Fig.48. In this figure, the swelling and shrinkage percentages of cushioned systems have been calculated based on the thickness of BC soil in each system.

The results of the experiments are shown in Table 6 for the case of full swelling-full shrinkage. The table reports the swollen and shrunken levels in each of the cycles for both BC and BC + CNS systems. In order to examine whether or not the CNS has been active, the figures for BC + Dummy (to account for replacement effect) system have been added. These refer to a system having BC and dummy cushion material which neither swells nor shrinks in any of the cycle, the thickness being unaltered. Since thickness of BC in BC + CNS system, is 2/3rd of thickness of system having BC alone, the figures for BC + dummy system will simply be 2/3rd of those of BC alone.

Now consider values corresponding to surcharge level of 5 kN/m^2. In the first cycle, swelling of BC+CNS is 8.67% as against 13% for the BC + dummy system, clearly showing an improvement of 4.33%. But at the end of 3rd cycle BC + CNS system is showing higher displacements in both swelling and shrinkage than the BC + dummy system. In fact in the second cycle itself, the shrinkage displacement of BC + CNS system is more than BC + dummy system. If the values were to be the same between the two, it means CNS is just inactive. If the displacement (ΔH) values of BC + CNS system are less, then CNS is advantageously active. If the values are more as have been seen in the third cycle and onwards, then BC + CNS behaviour is worse than that of BC alone.

Table 6 : Cyclic Behaviour of BC and BC+CNS Systems under Full Swelling—Full Shrinkage

Surcharge kN/m²	Description	First cycle				Second cycle				Third cycle			
		Displacement Level (%)		ΔH (%)		Displacement Level (%)		ΔH (%)		Displacement Level (%)		ΔH (%)	
		SW Level (%)	SH Level (%)	SW Level (%)	SH Level (%)	SW Level (%)	SH Level (%)	SW Level (%)	SH Level (%)	SW Level (%)	SH Level (%)	SW Level (%)	SH Level (%)
5.0	BC	19.50	1.00	19.50	18.50	20.00	8.00	19.00	12.00	19.00	8.50	11.00	11.50
	BC+DM	13.00	0.67	13.00	12.33	13.33	5.33	12.66	8.00	12.67	5.67	7.34	7.00
	BC+CNS	8.67	−1.33	8.67	10.00	8.67	0.00	10.00	8.67	9.34	1.33	9.34	8.00
50.0	BC	4.50	−11.50	4.50	16.00	0.50	−11.20	12.00	11.70	−1.50	−11.20	9.70	9.50
	BC+DM	3.00	−7.67	3.00	10.66	0.33	−7.47	8.00	7.80	−1.00	−7.47	6.47	6.47
	BC+CNS	2.00	98.67	2.00	10.67	−1.33	−9.47	7.34	8.14	−2.67	−9.47	6.80	6.80
100.0	BC	0.50	−13.50	0.50	14.00	−4.00	−15.00	9.50	11.00	−5.00	−15.50	10.00	10.50
	BC+DM	0.33	−9.00	0.33	9.33	−2.67	−10.00	6.33	7.33	−3.33	−10.33	6.67	7.00
	BC+CNS	0.15	−10.33	0.15	10.48	−4.00	−11.33	6.33	7.33	−4.67	−12.00	6.67	7.33
200.0	BC	−1.00	−16.00	1.00	15.00	−9.00	−19.00	7.00	10.00	−11.00	−21.00	8.00	10.00
	BC+DM	−0.67	−10.67	0.67	10.00	−6.00	−12.67	4.67	6.67	−7.33	−14.00	5.34	6.67
	BC+CNS	−0.67	−11.00	0.67	10.33	−6.67	−14.00	4.33	7.33	−8.00	−14.67	6.00	6.67

SW – Swollen   SH – Shrunken   DM – Dummy

Table 6 : Continued

Surcharge kN/m²	Description	Fourth cycle				Fifth cycle				Sixth cycle			
		Displacement Level (%)		ΔH (%)		Displacement Level (%)		ΔH (%)		Displacement Level (%)		ΔH (%)	
		SW Level (%)	SH Level (%)	SW Level (%)	SH Level (%)	SW Level (%)	SH Level (%)	SW Level (%)	SH Level (%)	SW Level (%)	SH Level (%)	SW Level (%)	SH Level (%)
5.0	BC	19.00	8.80	10.50	10.20	19.00	8.80	10.20	10.20	19.00	8.80	10.20	10.20
	BC+DM	12.67	5.86	7.00	6.81	12.67	5.87	6.81	6.80	12.67	5.87	6.81	6.81
	BC+CNS	9.87	2.33	8.54	7.54	9.87	2.33	7.54	7.54	9.87	2.33	7.54	7.54
50.0	BC	−1.80	−11.20	9.40	9.40	−1.80	−11.00	9.40	9.40	−1.80	−11.00	9.40	9.40
	BC+DM	−1.20	−7.47	6.27	6.27	−1.20	−7.47	6.27	6.27	−1.20	−7.47	6.27	6.27
	BC+CNS	−2.93	−9.47	6.54	6.54	−2.93	−9.47	6.54	6.54	−2.93	−9.47	6.54	6.54
100.0	BC	−6.90	−15.70	8.60	8.80	−6.90	−15.70	8.80	8.80	−6.90	−15.70	8.80	8.80
	BC+DM	−4.60	−10.47	5.73	5.87	−4.60	−10.47	5.87	5.87	−4.60	−10.47	5.87	5.87
	BC+CNS	−5.73	−12.13	6.27	6.40	−5.73	−12.13	6.40	6.40	−5.73	−12.13	6.40	6.40
200.0	BC	−13.00	−22.30	8.00	9.30	−14.33	−22.30	7.97	7.97	−14.33	−22.30	7.97	7.97
	BC+DM	−8.67	−14.87	5.33	6.20	−9.55	−14.87	5.31	5.31	−9.55	−14.87	5.30	5.30
	BC+CNS	−9.33	−15.33	5.34	6.33	−10.20	−15.67	5.13	5.47	−10.20	−15.67	5.44	5.44

SW — Swollen   SH — Shrunken   DM — Dummy

Consider the values corresponding to surcharge of 50 kN/m^2. The figures in the Table 6 clearly show that by 3rd cycle onwards, CNS is inactive. Similar comparisons at higher surcharges demonstrate that CNS is either inactive or helps in worsening the cyclic behaviour except in the first swelling. The value at all the salient levels with the type of movement is tabulated in Table 7. For the tests conducted, four types of swell-shrink movements viz., Type A, B, D & E have been observed. In all these cases highest displacement level occurred during the first swelling.

Comparing extreme displacement values (given in column 5), it clearly shows that under higher surcharges BC + CNS system will show more values than those for BC alone, accounting for replacement effect. Equilibrium bandwidth values shown in column 8 also unmistakably show that there is no reduction in equilibrium bandwidth in BC + CNS system after accounting for replacement effect.

The swollen and shrunken levels recorded for the cyclic tests conducted under the pattern of full swelling-partial shrinkage are shown in Table 8. The results for three cushion materials, CNS, CNS (NS1), and CNS (NS2) are shown in this table. Making comparisons described earlier, it is clear that even here, by 2nd cycle onwards the CNS has a tendency to become inactive. The alternatives to CNS, viz., CNS (NS1) and CNS (NS2) also do not show any marked improvement over the CNS behaviour. The value at all salient levels are recorded in Table 9. Advantage got in first swelling level seems to be essentially holding in all the cycles.

Heave and Shrinkage Profiles

The field heave and shrinkage of the ground at the surface and at different depths are usually known by actual measurements of the movements made over a period of time with different techniques such as Heave plugs or heave plates (Johnson, 1980), Multirod gauges with bearing plates placed in auger holes (Zeitlen and Komornik, 1961), Loaded pads (Freeman et al., 1992), Level pegs (De Bruijn, 1973), etc. Heave and shrinkage profiles can also be obtained by insitu soil suction measurements or approximately by empirical information by knowing the field capacity and assumed soil suction during dry seasons (Hamberg, 1985; Wray, 1987; Terazaghi el al., 1996). In addition the results of laboratory oedometer swell-shrink tests can also be used in generating heave and shrinkage profiles with depth based on the method suggested by Kassif and Zeitlen (1961).

The basic assumptions involved in this method are the following:

i)   Swelling and shrinkage is uniform in each layer.

Table 7 : Swell-Shrink Movements of BC and BC + CNS Systems under Full Swelling-Full Shrinkage

Surcharge kN/m²	Description	Highest Swollen Level (%)	Lowest Shrunken Level (%)	Extreme Displ. (%)	Equilibrium Swollen Level (%)	Equilibrium Shrunken Level (%)	Equilibrium Bandwidth (%)	Operating Displ. (%)	Type of Movement
5.0	BC	20.00	1.00	20.00	19.00	8.80	10.20	13.90	A
	BC+DM	13.33	0.67	13.33	12.67	5.87	6.80	9.27	A
	BC+CNS	8.67	−1.33	10.00	9.87	2.33	7.54	6.13	B
50.0	BC	4.50	−11.50	16.00	−1.80	−11.20	9.40	−6.50	D
	BC+DM	3.00	−7.67	10.67	−1.20	−7.47	6.27	−4.33	D
	BC+CNS	2.00	−9.33	11.33	−2.93	−9.47	6.53	−6.20	D
100.0	BC	0.50	−15.70	16.20	−6.90	−15.70	8.80	−11.30	D
	BC+DM	0.33	−10.47	10.80	−4.60	−10.47	5.87	−7.53	D
	BC+CNS	0.15	−12.33	12.48	−5.73	−12.13	6.40	−8.93	D
200	BC	−1.00	−22.30	22.30	−14.30	−22.30	8.00	−18.30	E
	BC+DM	−0.67	−14.87	14.87	−9.53	−14.57	5.33	−12.20	E
	BC+CNS	−0.67	−15.67	15.67	−10.20	−15.67	5.47	−12.93	E

Disp. − Displacement

Table 8 : Cyclic Behaviour of BC and BC + Cushion System under Full Swelling-Partial Shrinkage

Surcharge kN/m²	Description	First cycle				Second cycle				Third cycle			
		Displacement Level (%)		ΔH (%)		Displacement Level (%)		ΔH (%)		Displacement Level (%)		ΔH (%)	
		SW Level (%)	SH Level (%)	SW Level (%)	SH Level (%)	SW Level (%)	SH Level (%)	SW Level (%)	SH Level (%)	SW Level (%)	SH Level (%)	SW Level (%)	SH Level (%)
5.00	BC	19.00	7.00	19.00	12.00	12.60	7.60	5.60	5.00	12.60	7.60	5.00	5.00
	BC+DM	12.67	4.67	12.67	8.00	8.40	5.07	3.73	3.33	8.40	5.07	3.33	3.33
	BC+CNS	8.33	2.67	8.33	5.67	6.27	3.07	3.60	3.20	6.27	3.07	3.20	3.20
	CNS (NS1)	10..67	4.00	10.67	6.67	7.20	4.27	3.20	2.93	7.20	4.27	2.93	2.93
	CNS (NS2)	7.33	2.00	7.33	5.33	5.67	2.53	3.67	3.14	5.67	2.53	3.14	3.14
50.0	BC	4.50	1.25	4.50	3.25	3.25	1.50	2.00	1.75	3.25	1.75	1.75	1.75
	BC+DM	3.00	0.83	3.00	2.17	2.17	1.00	1.34	1.17	2.17	1.17	1.17	1.17
	BC+CNS	2.17	0.67	2.17	1.50	2.17	0.67	1.50	1.50	2.17	0.67	1.50	1.50
	CNS (NS1)	2.50	0.83	2.50	1.67	1.60	0.73	0.83	0.87	1.60	0.73	0.87	0.87
	CNS (NS2)	1.67	0.53	1.67	1.14	1.53	0.53	1.00	1.00	1.53	0.53	1.00	1.00

SW — Swollen   SH — Shrunken   DM — Dummy

Table 8 : Continued

Surcharge kN/m^2	Description	First cycle				Second cycle				Third cycle			
		Displacement Level (%)		ΔH (%)		Displacement Level (%)		ΔH (%)		Displacement Level (%)		ΔH (%)	
		SW Level (%)	SH Level (%)	SW Level (%)	SH Level (%)	SW Level (%)	SH Level (%)	SW Level (%)	SH Level (%)	SW Level (%)	SH Level (%)	SW Level (%)	SH Level (%)
5.00	BC	12.60	7.60	5.00	5.00	12.60	7.60	5.00	5.00	12.60	7.60	5.00	5.00
	BC+DM	8.40	5.07	3.33	3.33	8.40	5.07	3.33	3.33	8.40	5.07	3.33	3.33
	BC+CNS	6.27	3.07	3.20	3.20	6.27	3.07	3.20	3.20	6.27	3.07	3.20	3.20
	CNS (NS1)	7.20	4.27	2.93	2.93	7.20	4.27	2.93	2.93	7.20	4.27	2.93	2.93
	CNS (NS2)	5.67	2.53	3.14	3.14	5.67	2.53	3.14	3.14	5.67	2.53	3.14	3.14
50.00	BC	3.25	1.75	1.75	1.75	3.25	1.75	1.75	1.75	3.25	1.75	1.75	1.75
	BC+DM	2.17	1.17	1.17	1.17	2.17	1.17	1.17	1.17	2.17	1.17	1.17	1.17
	BC+CNS	2.17	0.67	1.50	1.50	2.17	0.67	1.50	1.50	2.17	0.67	1.50	1.50
	CNS (NS1)	1.60	0.73	0.87	0.87	1.60	0.73	0.87	0.87	1.60	0.73	0.87	0.87
	CNS (NS2)	1.53	0.53	1.00	1.00	1.53	0.53	1.00	1.00	1.53	0.53	1.00	1.00

SW – Swollen   SH – Shrunken   DM – Dummy

Table 9 : Swell-Shrink Movements of BC and BC + Cushion Systems under Full Swelling-Partial Shrinkage

Surcharge kN/m^2	Description	Highest Swollen Level (%)	Lowest Shrunken Level (%)	Extreme Displ. (%)	Equilibrium Swollen Level (%)	Equilibrium Shrunken Level (%)	Equilibrium Bandwidth (%)	Operating Displ. (%)	Type of Movement
5.00	BC	19.0	7.0	19.0	12.6	7.6	5.0	10.1	A
	BC+DM	12.67	4.67	12.67	8.40	5.07	3.33	6.73	A
	BC+CNS	8.33	2.67	8.33	6.27	3.07	3.20	4.67	A
	CNS (NS1)	10.61	4.27	10.61	7.20	4.27	2.93	4.67	A
	CNS (NS2)	7.33	2.53	7.33	5.67	2.53	3.14	4.07	A
50.0	BC	4.5	1.25	4.50	3.3	1.5	1.8	2.4	A
	BC+DM	3.00	0.83	3.00	2.20	1.00	1.20	1.60	A
	BC+CNS	2.17	0.67	2.17	1.67	0.67	1.00	1.17	A
	CNS (NS1)	2.50	0.73	2.50	1.60	0.73	0.87	1.20	A
	CNS (NS2)	1.67	0.53	1.67	1.53	0.53	1.00	1.03	A

Disp. — Displacement

ii)   Active depth within which moisture content fluctuation takes place which
        in turn induces heave or shrinkage considered invariant with cycles.
iii)   The wet density of soil remains constant for both dry and wet seasons.
iv)   Any soil replacing the expansive soil will also have the wet density
        same as the expansive soil.

Two cases are considered to illustrate the method.

CASE I: A footing in an expansive soil at a depth of 2m below ground

        Fig.49 shows the ground profile for the problem in question for a
footing $1.5 \times 1.5m$ size under a pressure of $150 \, kN/m^2$, assuming 3m thick
active zone (divided into 3 layers of each 1m thick) below the footing level.
Full swelling-full shrinkage pattern is assumed in all the layers.

        From the laboratory swell-shrink tests corresponding to the above
patterns, vertical swell percentage versus surcharge for each cycle under
consideration can be plotted. Fig.50 shows the plot of vertical displacement
versus pressure for the first, second and the equilibrium cycles. ΔH for each
layer is read from the Fig.50 and taking H_i equal to layer thickness, heave
or shrinkage is calculated as shown in Table 10. For this particular problems
for the pressure ranges of interest all vertical displacements are negative. As
all values are negative, the negative signs are dropped from Table 10. These
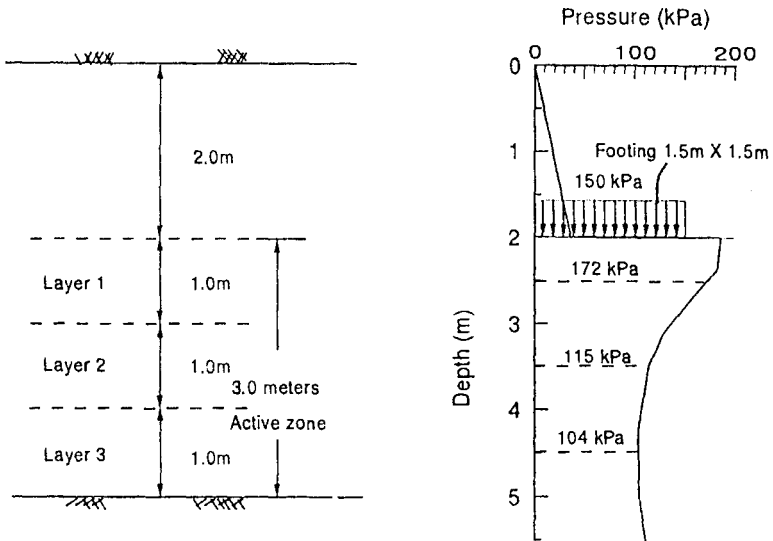results are plotted in Fig.52.

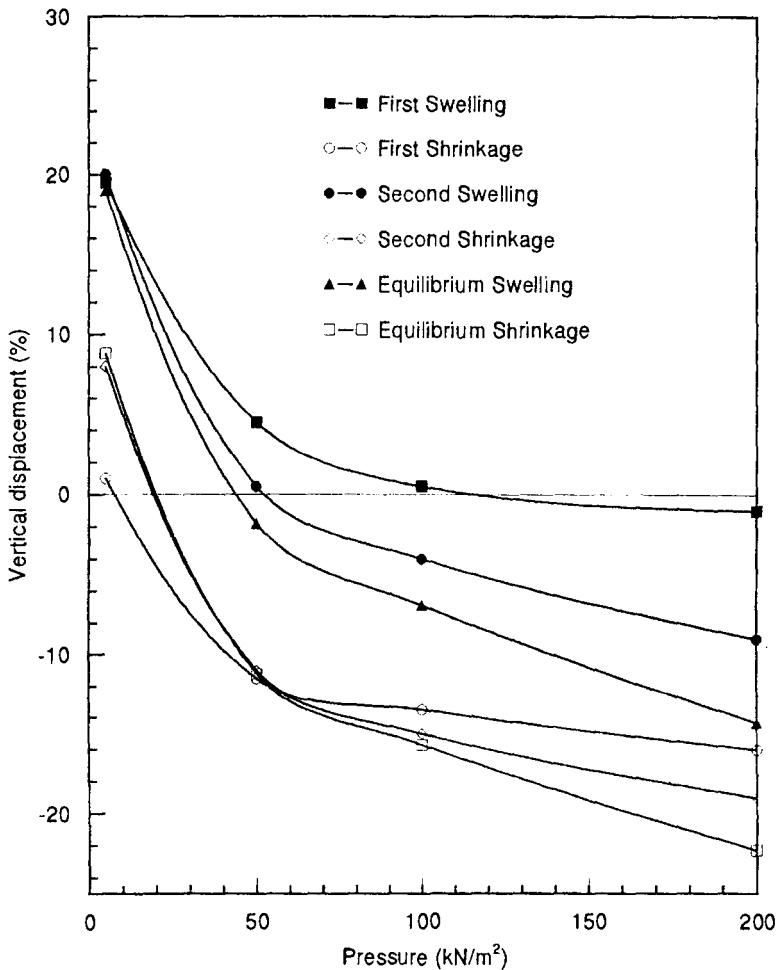FIGURE 49 : Square Footing at 2.0m Depth

FIGURE 50 : Pressure Displacement Plots with Cycles for BC Soils (Full Swelling - Full Shrinkage)

CASE II: A footing at a depth of 2m below ground with a CNS cushion of 1.0m thickness

Fig.51 shows the laboratory test data for the first, second and for the equilibrium cycles for BC + CNS system. The calculations for BC + CNS system are shown in Table 11. Heave and shrinkage values in the first, second and at equilibrium cycles have been calculated and profiles marked in Fig.52.

For the system having 3m of only BC, cumulative heave or shrinkage at equilibrium state is seen to be 253mm. The same gets changed to 184mm

Table 10 : Heave and Shrinkage Calculations for Black Cotton Soil

Layer	Pressure kN/m²	First cycle				Second cycle				Eq. cycle			
		Heave	Cum. Heave	SH	Cum. SH	Heave	Cum. Heave	SH	Cum. SH	Heave	Cum. Heave	SH	Cum. SH
1	172.0	8.0	7.5	143.0	418.0	71.5	247.5	99.00	313.5	82.5	253.0	82.5	253.0
2	115.0	2.5	0.5	137.5	275.0	88.0	176.0	104.5	214.5	82.5	170.5	82.5	170.5
3	104.0	3.0	3.0	137.5	137.5	88.0	88.0	110.0	110.0	88.0	88.0	88.0	88.0

Cum. – Cumulative   SH – Shrinkage

All values in mm

Table 11 : Heave and Shrinkage Calculations for BC + CNS Soil System

Layer	Pressure kN/m²	First cycle				Second cycle				Eq. cycle			
		Heave	Cum. Heave	SH	Cum. SH	Heave	Cum. Heave	SH	Cum. SH	Heave	Cum. Heave	SH	Cum. SH
1	172.0	4.0	6.0	104.0	312.0	50.0	172.0	74.0	218.0	58.0	184.0	58.0	184.0
2	115.0	2.0	2.0	104.0	208.0	60.0	122.0	72.0	144.0	62.0	126.0	62.0	126.0
3	104.0	0.0	0.0	104.0	104.0	62.0	62.0	72.0	72.0	64.0	64.0	64.0	64.0

Cum. – Cumulative   SH – Shrinkage
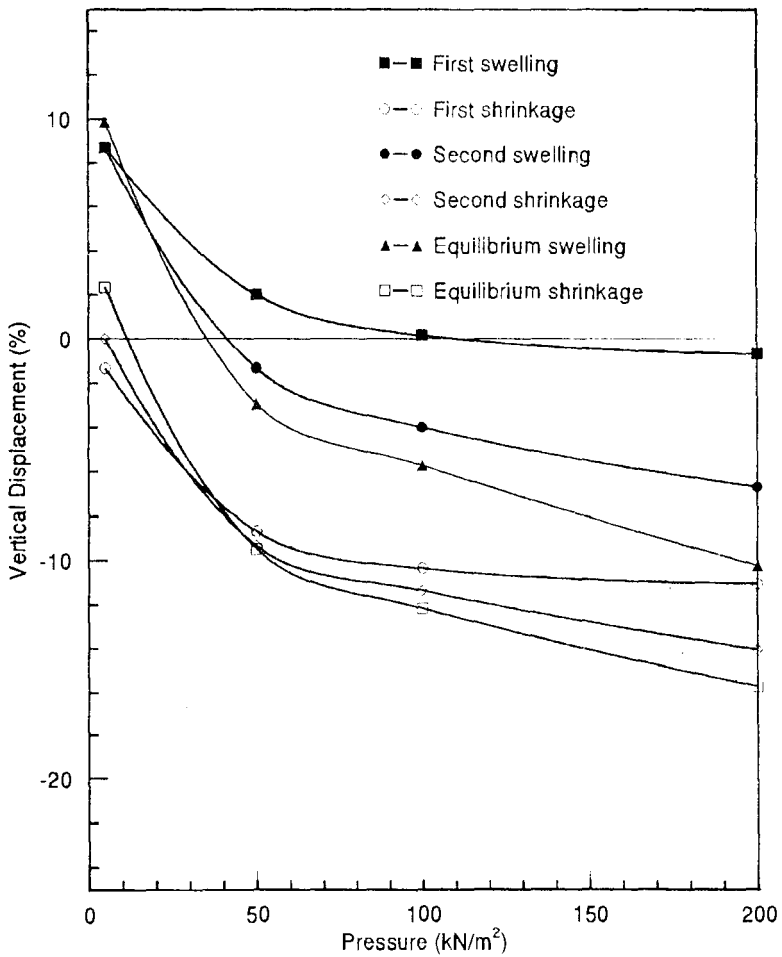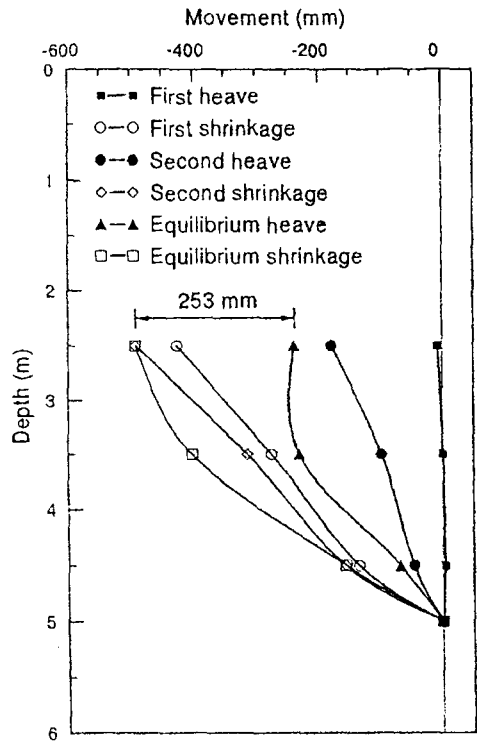
All values in mm

**FIGURE 51 : Pressure Displacement Plots with Cycles For BC+CNS Soils
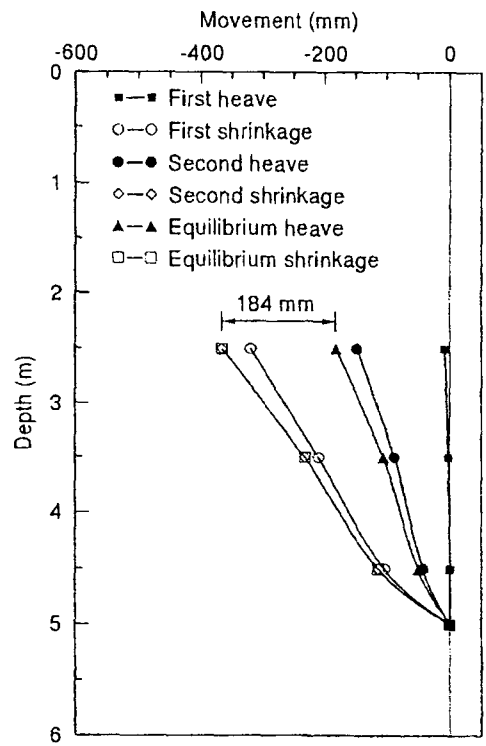(Full Swelling - Full Shrinkage)**

if 1m of black cotton soil were to be replaced by a CNS layer. Had an inactive layer of the same thickness replaced it, the corresponding value would have been $2/3^{rd}$ of 253mm, which is equal to 169mm. Therefore clearly replacement by CNS has worsened the situation.

Conclusions

The real challenge about the expansive soils is their ability to undergo very large movements, the uncertainties of which render any rational design most difficult. Reasonable assessment of swell-shrink pattern coupled with laboratory cyclic tests will help a great deal in understanding possible heaves

FIGURE 52 : Heave and Shrinkage Profiles for Square Footing

and settlements. The possible movements have been classified into five types, types A to E. The experimental results have clearly demonstrated that the swell-shrink behaviour of expansive soils is different in different cycles. After a few cycles however, the soil will come under steady movements. The studies have brought out that the equilibrium bandwidth associated with steady movements can be assessed fairly reliably since it possesses certain uniqueness. It is seen not only unaffected by the placement conditions but also by the swell-shrink sequence.

Studies reported in this paper have highlighted that the expansive soils exhibit memory. When a soil that is in equilibrium under a particular swell-shrink pattern is disturbed and comes under the influence of a new pattern, a new equilibrium will follow after a few cycles. If the old pattern is once again restored, the old bandwidth will again get re-established. This re-establishment of bandwidth takes place as long as the immediate shrunken level does not exceed the maximum past shrunken level. The shrunken levels, present and the past, are the controlling factors in defining the cyclic behaviour and also for the presence or absence of the fatigue phenomenon. If the past shrunken level is not exceeded in the changing patterns, there will be no fatigue.

Most of the earlier research on the cyclic behaviour has indicated that the swell potential in the second cycle (swelling following the first shrinkage) is usually the maximum. The reason has been attributed to the particle arrangement. The results presented in this paper have shown that a set of placement conditions (points on 83% S_r line and the dry densities less than or equal to Proctor maximum) bring about the invariance of the swell potentials with cycles. Measurements of shear strength of swollen specimen show that the swollen soils still possess significant shear strengths. Even though the soil is fully saturated at the swollen level the saturation water content will be just about 50% of the liquid limit water content.

The swelling and shrinkage are two different magnitudes and processes at the beginning. After four or five cycles, when the equilibrium state is reached, the two magnitudes become the same and the swelling and shrinkage become reversible.

The compacted specimens and the desiccated specimens expectedly show significant differences in their behaviour. The vertical swell potentials of desiccated soils are unaffected by compaction water contents or dry densities, the same as observed in the name of Bandwidth. But the volumetric swell potential increases with increase in the initial void ratio of the soil. More the initial void ratio, more would be the reduction in the cross-sectional area of the desiccated specimen and more would be the volumetric swell potential.

Swell-shrink behaviour of CNS-cushioned expansive soil clearly demonstrates that the CNS becomes less and less active and effective with cycles. CNS soil definitely helps in absorbing some swelling potential in the first cycle. Afterwards, the performance of BC + CNS system becomes less impressive and may even become worse than that of BC alone.

Acknowledgements

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