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Technical Note

Influence of cyclic wetting drying on collapse behaviour of compacted residual soil

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Abstract. The climatic zones where residual soils occur are often characterized by alternate wet and dry seasons. Laboratory studies of earlier workers have established that the alternate wetting and drying process affects the swell-shrink potentials, water content, void ratio and particle cementation of expansive soils. The influence of cyclic wetting and drying on the collapse behaviour of residual soils has not been examined. This paper examines the influence of alternate wetting and drying on the collapse behaviour of compacted residual soil specimens from Bangalore District. Results of such a study are useful in anticipating changes in collapse behaviour of compacted residual soil fills. Experimental results indicated that the cyclic wetting and drying process increased the degree of expansiveness of the residual soils and reduced their collapse tendency. Changes in the swell/collapse behaviour of compacted residual soil specimens from wetting drying effects are attributed to reduction in water content, void ratio and possible growth of cementation bonds.

Key words. collapse, residual soils, swell, wetting and drying.

1. Introduction

Studies examining the effect of cyclic wetting and drying on swell–shrink characteristics of compacted expansive soils have bring out that alternate wetting and drying causes the water content and void ratio of the expansive soils to vary between near constant limits and effects particle cementation (Blight, 1966; Grant, 1974; Allam and Sridharan, 1981; Sridharan and Allam, 1982; Chen and Ma, 1987; Subba Rao and Satyadas, 1987; Dif and Blumel, 1991; Day, 1994; Al-Homoud et al., 1995, Subba Rao et al., 2000).

In addition to heave, residual soils in semi-arid climatic zones also exhibit collapse phenomenon (Barksdale and Blight, 1997). The phenomenon of collapse settlement occurs in two types of residual soils. The first category of collapsing residual soils is believed to be transported soils that have undergone post-depositional pedogenesis. An example of this soil type is the sandy soils occurring in Southern Africa (Jennings and Knight, 1957). The second category of collapsing residual soils is the highly

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weathered and leached residual soils. Because of leaching and loss of mineral matter, the residual soil becomes silty or clayey sand with a high void ratio and collapsible grain structure. Examples of this category of collapsing soils are residually derived red soils formed by the mechanical and chemical decomposition of gneiss and basalt rocks (Vargas, 1973; Barksdale and Blight, 1997; Rao and Revanasiddappa 2002).

The impact of cyclic wetting and drying on the collapse behaviour of residual soils has not been examined. Such studies are useful to understand the possible changes in collapse behaviour of compacted residual soil fills that are subject to periodic wetting and drying from climatic variations This paper examines the influence of alternate wetting and drying on the collapse behaviour of compacted residual soil specimens from Bangalore District. To promote collapse the residual soil specimens were compacted to a medium degree of compaction (relative compaction = 84%).

2. Materials and methods

2.1. SOIL DESCRIPTION

The representative residual soil sample was collected at a depth of 1.0 m from Indian Institute of Science Campus, Bangalore and is locally referred to as red soil. The natural soil was sieved through a 425 μm sieve prior to determining its index properties, compaction characteristics (Table 1) and collapse potential. X-ray diffraction pattern of the # 75 μm fraction showed that the representative soil contains kaolinite and montmorillonite as its major and minor clay minerals respectively. Quartz, mica and feldspar comprise the non-clay mineral fraction of this soil.

2.2. COMPACTED SPECIMENS

2.2.1. *Preparation*

Air-dried representative soil specimens were thoroughly hand-mixed with the design water contents and allowed to equilibrate for 24 h in sealed polythene covers. The

Table 1. Index properties of residual soil

Property	Value
Specific gravity	2.71
Liquid limit (%)	37
Plastic limit (%)	19
Plasticity index (%)	18
Grain size distribution (%)	
Sand	42
Silt	26
Clay	32
Unified soil classification symbol	CL
Standard Proctor Compaction characteristics	
Maximum dry density (Mg/m^3)	1.77
Optimum moisture content (%)	17.6

required mass of moisture-equilibrated specimens was carefully transferred to oedometer rings of 76 mm diameter and 25 mm height. The moist soil specimens were compacted to a dry density of 1.49 Mg/m^3 (relative compaction = 84%) using a hand-operated static press at water contents of 10.6% (7% dry of OMC), 17.6% (OMC) and 26.4% (8.8% wet of OMC). Specimens compacted at water contents of 10.6%, 17.6% and 26.4% belong to series 1, series 2 and series 3 respectively.

2.2.2. *Collapse potential measurement*

Series 1, 2 and 3 specimens were evaluated for their collapse potentials at vertical stresses of 6.25, 50, 100 and 200 kPa respectively. A separate specimen was tested at each pressure. Thus, four specimens were tested in each series. Each specimen was incrementally loaded to the desired pressure and inundated with tap water. Time-collapse readings were continuously noted during the process. Most of the collapse events occurred in less than 60 min after inundation. The final deflection after 24 h was used to calculate the collapse potential to allow for any residual collapse of the specimen (Lawton et al., 1992). The swell or collapse potential of a compacted specimen was calculated from the equation:

$$\text{Swell/Collapse potential} = \frac{\pm\Delta e}{1 + e_{\text{unsoaked}}} \times 100\% \tag{1}$$

Where Δe represents the increase (for swelling condition) or decrease (for collapse condition) in void ratio (after 24 h) of the specimen on wetting under the desired pressure (6.25, 50, 100 and 200 kPa) and $e_{unsoaked}$ is the void ratio of the unsoaked specimen at that pressure. The term Δe assumes a positive sign when the sample swells, and a negative sign when the sample collapses.

2.3. CYCLICALLY WETTED AND DRIED SPECIMENS

2.3.1. *Wetting-drying procedure*

The compacted specimens were subjected to alternate wetting and drying cycles in modified oedometer assemblies consisting of an oedometer cell placed in a stainless steel jacket fitted with electrical Nichrome heating coil for maintaining an elevated temperature of 40 ± 3 °C, representative of the arid to semi-arid zone dry season temperatures. The temperature of the oedometer cell was maintained at 40 °C using a thermostat.

Series 1, 2 and 3 specimens were set up in the modified oedometer assemblies and inundated with tap water at 6.25 kPa. The compacted soil specimens completed most of their swelling in 30–60 min. However, the specimens were wetted for 24 h to complete any residual swelling. After 24 h, water in the oedometer cell was siphoned and the thermostat controlled heating system was switched on to dry the specimen at 40 ± 3 °C. Shrinkage of the specimens was inferred to be complete when the dial gauge readings became nearly constant after 48 h of drying. This processes constituted one wetting and drying cycle of a soil specimen.

Before starting the next cycle of wetting and drying, the heating system was switched off and the oedometer assembly was cooled to room temperature. The specimen was wetted for 24 h. After 24 h, water was siphoned from the oedometer cell and the specimen was dried at 40 °C for 48 h. Such cycles of alternate wetting and drying were repeated. Experiments revealed that the vertical swelling and shrinkage movements of the compacted specimens occurred between near constant limits of 1.6–2.3% after two or three wetting and drying cycles. Adopting a conservative approach, the compacted soil specimens were subjected to four wetting and drying cycles. The void ratio and water contents of the desiccated specimens (*specimens subjected to four cycles of wetting and drying at 6.25 kPa are referred as desiccated specimens)* are provided in Table 2. Shrinkage of the compacted residual soil specimen was accompanied by negligible (0.2%–1%) reduction in cross-sectional area (45.36 cm^2) during any drying cycle indicating that the specimens underwent shrinkage movements mainly in the vertical direction.

2.3.2. *Collapse potential determination*

The swell/collapse potentials of the desiccated specimens were evaluated at vertical stresses of 6.25, 50, 100 and 200 kPa respectively by the procedure detailed in Section 2.2.2.

3. Results and Discussion

3.1. COLLAPSE BEHAVIOUR OF COMPACTED SPECIMENS

Figure 1 presents the swell/collapse potentials of series 1–3 specimens as a function of applied load. Series 1 specimens marginally swell (1%) below 30 kPa and collapse at the higher loads. Series 2 specimens experience no volume change on wetting at 6.25 kPa and collapse on wetting at loads higher than 6.25 kPa. Comparatively, series 3 specimens experience no volume change on wetting up to 100 kPa and exhibit marginal ($< -0.5\%$) collapse at loads greater than 100 kPa. The decrease in

Table 2. Index properties of compacted and desiccated specimens

Series	Specimen state	Property		
		ρ_d (Mg/m^3)	w (%)	Void ratio
1	Compacted	1.49	10.6	0.81
1	Desiccated	1.51	2.0	0.78
2	Compacted	1.49	17.6	0.81
2	Desiccated	1.54	3.5	0.74
3	Compacted	1.49	26.4	0.81
3	Desiccated	1.66	5.5	0.62

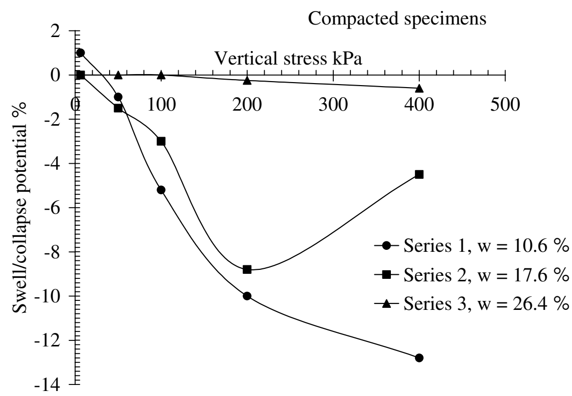

Figure 1. Collapse behaviour of compacted specimens.

collapse potential of the residual soil specimens with increase in compaction water content (Figure 1) under a given load is according to expectations (Cox, 1978; Lawton, et al., 1989). The reduction in collapse potentials of series 2 specimens at pressures larger than 200 kPa is due to substantial compression of the specimens prior to their wetting (Lawton et al., 1992).

3.2. EFFECT OF CYCLIC WETTING AND DRYING ON SWELL/COLLAPSE OF RESIDUAL SOIL SPECIMENS

Figure 2 compares the swell/collapse behaviour of series 1 specimens in the compacted state and after four cyclic wetting and drying. Four cycles of wetting and drying slightly reduced the void ratio (from 0.81 to 0.78) but caused a marked decrease in water content (from 10.6% to 2%) of this residual soil specimen (Table 2). The vertical loads at which the compacted and desiccated specimens experience no vertical deformations in Figure 2 represent the swelling pressure. Cyclic wetting and drying increased the swelling pressure of the series 1 specimen from 35 to

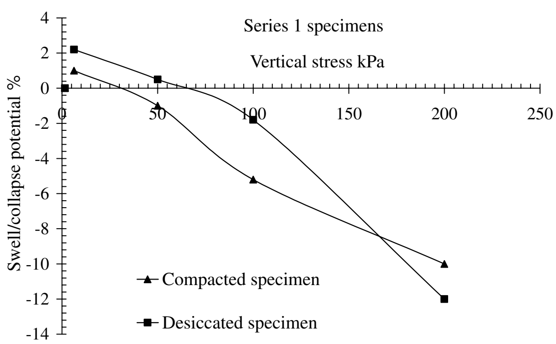

Figure 2. Collapse behavior of series 1 specimens in compacted and desiccated states.

60 kPa. The residual soil specimen collapses at 50 kPa (Figure 2) in the compacted state as its swelling pressure (35 kPa) is exceeded at this load. Comparatively, the desiccated specimen swells at 50 kPa as, its swell pressure (65 kPa) was not exceeded by the applied load (Figure 2). The desiccated specimens collapse less than the compacted specimens in the pressure range of 70–180 kPa.

The void ratio and water content of the series 2 specimens reduced from 0.81 to 0.74 and 17.6 to 3.5% respectively on cyclic wetting and drying (Table 2). Residual soil specimens belonging to series 2 exhibit a similar pattern as the series 1 specimens with respect to changes in swell/collapse behaviour on cyclic wetting and drying (Figure 3). The void ratios of the series 3 specimens are most affected as their void ratio reduced from 0.81 to 0.64 by the cyclic wetting and drying process. The water content of these specimens reduced from 26.4 to 3.5% after 4 cycles of wetting and drying (Table 2). Besides experiencing larger swelling strains at loads below the swell pressure (80 kPa), series 3 specimens collapses more in the desiccated state than in the compacted state at pressures $>$ 80 kPa (Figure 4). However, the magnitudes of collapse strains of the desiccated specimens are small (-0.5 to -2%).

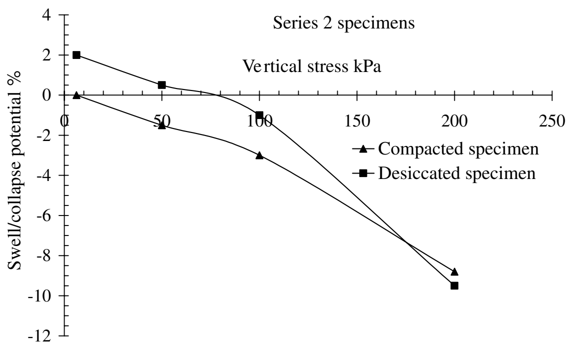

Figure 3. Collapse behavior of series 2 specimens in compacted and desiccated states.

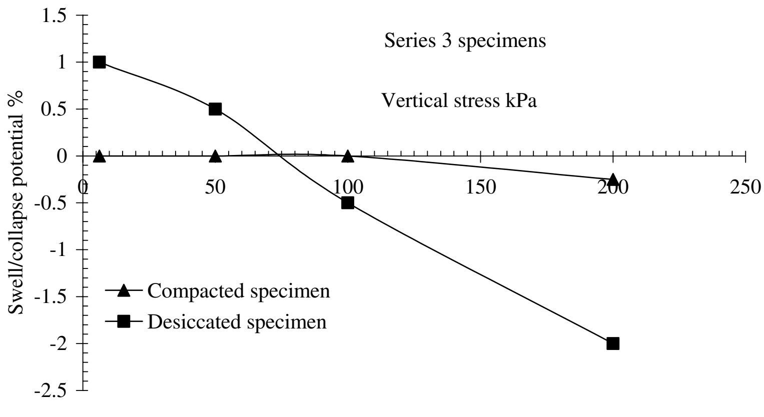

Figure 4. Collapse behavior of series 3 specimens in compacted and desiccated states.

3.3. CLASSIFICATIONS OF SWELL AND COLLAPSE POTENTIALS

Table 3 classifies the severity of swell of unsaturated soils based on their percent swell and swell pressure values (after Chen, 1988). Table 4 classifies the severity of collapse of unsaturated soils based on their percent collapse values (after Fookes, 1990). Table 5 classifies the degree of expansion of the residual soil specimens in the compacted and desiccated states according to Chen's (1988) classification. Table 6 classifies the severity of collapse of the residual soil specimens in the compacted and desiccated states according to Fookes (1990) classification. Data in Table 5 shows that cyclic wetting and drying transforms the low swelling residual soils to moderately expansive soils. Though the swell potentials marginally increased from 0–1% to

Table 3. Degree of soil expansion (after Chen, 1988)

Probable expansion,%	Swell pressure,	Degree of expansion
> 10	958	Very high
3–10	239–958	High
1–5	144–239	Medium
< 1	< 48	Low

Table 4. Severity of soil collapse (after Fookes, 1990)

Percent collapse	Severity of problem
0–1	No problem
1–5	Moderate trouble
5–10	Trouble
10–20	Severe trouble
20	Very severe trouble

Table 5. Degree of expansion of compacted and desiccated residual soil specimens

	Percent expansion at 6.25 kPa		Swell pressure, kPa		Degree of expansion (after Chen, 1988)	
Series	Compacted state	Desiccated state	Compacted state	Desiccated state	Compacted state	Desiccated state
1	1	2.2	30	65	Low	Medium
2	0	2	0	64	Low	Medium
3	0	1	0	70	Low	Medium

Table 6. Severity of collapse of compacted and desiccated residual soil specimens

	Percent collapse at 100 kPa		Severity of collapse (after Fookes, 1990)	
Series	Compacted State	Desiccated State	Compacted state	Desiccated state
1	−5.2	−1.8	Trouble	Moderate trouble
2	−3	−1	Moderate trouble	No problem
3	0	−0.5	No problem	No problem

1–2%, their swelling pressures notably increased from 0–30 kPa to 65–70 kPa. Comparison of Tables 5 and 6 show that cyclic wetting and drying has a stronger influence on the collapse potentials of the residual soil specimens. The collapse potentials of the compacted specimens show a three-fold reduction after 4 cycles of wetting and drying. Consequently, residual soils that classify as troublesome soils in the compacted state classify as moderately troublesome in the desiccated state. Similarly, residual soils that classify as moderately troublesome soils in the compacted state classify as non-problematic soils in the desiccated state.

3.4. HYPOTHESIS FOR REDUCED COLLAPSE MAGNITUDES OF DESICCATED SPECIMENS

The swell potentials of expansive soils increase with decrease in void ratio and water content. Comparatively, collapse potential of unsaturated soils decrease with reduction in void ratios and increase in water content (Dudley, 1970; Barden, et al., 1973; Foss, 1973; Cox, 1978; Popescu, 1986; Houston and Houston, 1988; Tadepalli and Fredlund, 1991; Nelson and Miller, 1991; Lawton et al., 1989; Rao and Revanasiddappa, 2000). The increased expansivity of the residual soil specimens in the desiccated state is commiserate with their reduced void ratio and water content (Table 2). The reduced void ratio of the desiccated residual soil specimens will tend to suppress their collapse tendency, while their decreased water contents would act to increase the same. The reduction in collapse tendency of the desiccated specimens (Figures 2 and 3) suggests that changes in void ratio dominate over water content changes.

Table 2 reveals that cyclic wetting and drying marginally decreased the void ratios of series 1 and 2 specimens by 4–9%. However a three-fold decrease occurred in the collapse potentials of the desiccated specimens (Table 6). It is therefore speculated that besides changes in void ratio an additional factor may have reduced the collapse potential of the desiccated residual soil specimens. Experimental results of earlier workers suggest that cyclic wetting and drying generate cementation bonds comprised of aluminum, iron, calcium and magnesium compounds in residual soil specimens (Grant, 1974; Gidigasu, 1976; Allam and Sridharan, 1981; Sridharan and Allam, 1982; Vaughan 1988; Han, 1995; Reddy, 1998). The strengthening of inter-particle contacts by cementation bonds may have offered additional resistance to local shear forces induced by the applied loads thereby lowering the collapse potentials of the desiccated residual soil specimens. Once the applied loads exceed this additional bond strength, the desiccated specimens tend to collapse more than the compacted specimens by virtue of their lower moisture contents (Figures 2–4).

3.4. PRACTICAL IMPLICATIONS OF RESULTS

The laboratory results suggest that residual soil fills subjected to cycles of wetting and drying in the field may develop higher swell pressures and reduced collapse tendency in relation to their compacted state because of changes in water content, void ratio and inter-particle cementation. Based on the range of swell and collapse potentials exhibited by laboratory specimens in the desiccated state (Tables 5 and 6), it is suggested that residual soil fills should be compacted on the wet side of OMC at a given dry density since, laboratory specimens compacted on the wet side of OMC exhibited marginal swell and collapse potentials (≤ 2%) after cycles of wetting and drying.

4. Conclusions

Cyclic wetting and drying increases the degree of expansiveness and reduces the collapse tendency of residual soil specimens. Though swell potentials of the compacted residual soil specimens showed a slight increase, their swell pressures significantly increased upon cyclic wetting and drying. The collapse potentials of the compacted residual soil specimens reduced by three-folds upon cyclic wetting and drying. The cyclic wetting and drying process reduced the void ratio and water content of the compacted residual soil specimens, which increased their expansivity. The reduction in collapse potential of the compacted residual soil specimens upon cyclic wetting and drying is attributed to reduction in void ratio and perhaps growth of cementation bonds. Based on laboratory results it is recommended that residual soil fills should be compacted on the wet side of OMC at a given dry density, as laboratory specimens compacted at this condition exhibited marginal swell and collapse potentials (≤ 2%) after cycles of wetting and drying.

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