京 都 大 学 防 災 研 究 所　年 報第47 号B　平成 16 年4 月
Annuals of Disas. Prev. Res. Inst., Kyoto Univ., No. 47 B, 2004

Collapse Potential and its Mechanism in Unsaturated Granular Soils

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Synopsis

Collapsible soils are moisture sensitive soils that induce volumetric compression on wetting. A major concern in utilizing compacted soil in civil engineering application is their potential to collapse when wetted under load. The investigation of wetting-induced volume change behavior of a compacted soil is one of the recent topic that has given due attention in the study of unsaturated soil mechanics. In this paper the mechanical behavior of a compacted granular soil is experimentally investigated. The behavior of volume changes are explored using a modified triaxial permeameter system where the stress state variables are independently controlled. Wetting stress paths are utilized to refelect field conditions associated with the rise in groundwater level in collapsible soil stratum under a certain constant isotropic loading. Measurments of total volume change and water content change are made. The experimental data are analyzed to investigate the collapse potential and its mechanism of unsaturated granular soils prepared at different initial conditions.

Keywords: collapse, wetting path, modified triaxial cell, matric suction, granular soil.

1. Introduction

Conditions in arid and semi-arid climates favor the formation of the most problematic moisture-sensitive arid soils (such as expansive soils, and collapsible soils). Moisture sensitive soils earn their name by swelling, collapsing or losing their strength when wetted. Swelling occurs when the soil is plastic, initialy dry and lightly confined, while collapse occurs when the soil is non-plastic, initialy dry and relatively heavily confined. In this research, emphasis will be placed on moisture sensitive soils exhibiting collapse upon wetting (i.e., collapsible soils). Construction in and on these soils needs thorough investigation of their behavior when wetted.

In the study of collapse from unsaturated soil point of view, many tests and investigation are done using fine-grained specimens (like silt & clay), merely for the reason that the effect of suction changes are observed more clearly in clay specimens than the test result obtained by granular soil specimens. Nevertheless, granular soil is an interesting material in which suction effect can be clearly imagined as primarily acting as a meniscus mechanism. In this sense the capillary concept provides a simplified insight into the mechanism leading to large scale response (i.e., macroscopic phenomenon), such as collapse behavior, and shrinkage behavior of soil.

In real stratum, layers made from or predominantly consist of granular soils (sand, silt) do exist, and this stratum usually found in meta-stable state depending on the formation of the deposit, and are usually known as collapsible soils. Therefore, the investigation of the mechanical behavior of granular soil in relation to suction change (wetting stress path) is a necessary task in the study of some geotechnical problems.

The change in volume of the soil resulting from changes in soil suction has been the object of many geotechnical research studies in the last few years (Tadepalli *et al.* 1991, 1992; Jose *et al.* 2000; Rao *et al.* 2002; Kohgo *et al.* 1997; Houston *et al.* 2001, Escari *et al.* 1973).

It is commonly assumed that only sandy or silty soils exhibit collapse; however, in recent years it has been reported that compacted soil in general can exhibit collapse (Barden *et al.* 1973; Cox 1978). Naturally existing unsaturated granular soils, like loess and meta-stable foundation layer found above groundwater level, or man-made earth structures such as embankments, road fills, and earth dams often exhibits collapse when compacted dry-of-optimum (Holtz 1948). Clayton (1980) reported the occurrence of collapse in compacted chalk-fill.

It is now generally accepted that any type of soil compacted dry-of-optimum may develop a collapsible fabric or meta-stable structure at low densities and high confining stress.

According to most researchers (eg. Dudley (1970), and Barden *et al.* 1973), four factors are said to be needed to produce the collapse in a soil structure:

- An open, partially unstable, unsaturated fabric
- A high enough net total stress that will cause the structure to be meta-stable.
- The existance of a bonding or cementing agent that stabilizes the soil in the unsaturated condition.
- The addition of water to the soil, which causes the bonding or cementing agent to be reduced and the inter-aggregate or inter-granular contact to fail in shear, resulting in reduction in total volume of the soil mass.

The main objective of this paper is to experimentally investigate the wetting-induced volume change behavior of granular soils compacted at meta-stable condition, and proving the necessity of the above four factors as a cause for occurance of collapse in the soil.

2. Collapsible soils

Arid soils in general are moisture-sensitive soils. Moisture-sensitive soils earn their name by swelling, collapsing, or losing strength when they came in contact with water. Volume change upon wetting is either swell (if the material is plastic, initially dry, and lightly confined) or collapse (if the material is non-plastic or slightly plastic, initially dry, and heavily confined). In this paper emphasis will be placed on moisture-sensitive soils exhibiting collapse upon wetting.

Structural stability is imparted to a collapsible soil by matric suction that stabilizes the inter-granular contacts in the partially structured condition. Addition of water weakens the capillary bonds and causes the inter-granular contacts to fail in shear, resulting in a reduction in total volume.

The prediction of the performance of a collapsing earth structure in engineering practice requires the modeling of the collapsible soil behavior from a macroscopic viewpoint. Such an approach allows for the use of the theory of unsaturated soil mechanics in the prediction of the collapsing behavior of soils. Alonso (1993) stated that the microstructure is widely recognized as important information in explaining the behavior of collapsing soils despite the fact that it lacks a simple quantitative descriptor.

Currently, regarding the behavior of moisture-sensitive soils exhibiting collapse upon wetting, geotechnical engineer recognizes that:

- Any type of soil compacted at "dry-of-optimum" conditions and at a low dry density may develop a collapsible fabric or meta-stable structure (Barden *et al.* 1969, 1973).
- A compacted and meta-stable soil structure is supported by micro-forces of shear strength (i.e., bonds) that are highly dependent upon capillary action. The bonds start losing strength with the increase of water content and at a "critical degree of saturation" the soil structure collapses (Jennings and Knight 1957; Barden *et al.* 1973).
- There is a gradual increase in compressibility as well as a gradual decrease in shear strength of a collapsible soil during the saturation process (Jennings and Burland 1962; Barden *et al.* 1973).
- The soil collapse progresses as the degree of saturation increases. There is, however, a critical degree of saturation for a given soil above which negligible collapse will occur regardless of the magnitude of the pre-wetting overburden pressure (Jennings and Burland 1962; Houston *et al.* 1993).
- The collapse of a soil is associated with localized shear failures rather than an overall shear failure of the soil mass (Maswoswe 1985).
- During wetting-induced collapse, under a constant vertical load and under K_0-oedometer condition, a soil specimen undergoes an increase in horizontal stresses (Maswoswe 1985).
- In collapse mechanism, at a given net confining pressure and following a wetting stress path, the metastable-structured soils follows three distinct phases in terms of total deformations with a decrease in matric suction: the pre-collapse, the collapse, and the post-collapse phase (Jose, *et al.* 2000)

- During the application of wetting stress path on compacted granular soils, collapse is believed to be initiated/commenced as the soil suction approaches its air entry suction (Shemsu 2003).

- Soil that experiences collapse will possess more shear strength than before undergoing collapse, if sheared at equal matric suction (Shemsu *et al.* 2003, Shemsu 2003).

- Under a triaxial stress state, the magnitude of volumetric strain, resulting from a change in stress state or from wetting, depends on the mean normal total stress and is independent of the principal stress ratio (σ_a/σ_r). However, the individual component of volumetric station (i.e., axial and radial station) depends on the principal stress ratio. For a given mean normal total stress, the magnitude of axial collapse increases and the magnitude of radial collapse decrease with an increasing stress ratio (Lawton *et al.* 1991).

The last observation provides valuable information for the modeling of the collapsing soil behavior, as it relates the total volumetric wetting-induced collapse to the mean net normal total stress. It illustrates that a collapsing soil can even undergo expansion in the direction of the minor total stress during saturation, depending on the applied stress ratio. Isotropic wetting-induced soil collapse can occur on a soil specimen under an isotropic total stress state. In addition, it predicts that during tri-axial wetting-induced collapse a soil specimen undergoes stress-induced anisotropic deformations that are functions of the applied anisotropic stress state.

3. The Test Program and Procedure

The testing program was designed with the main objective of analysing the mechanical behavior of a compacted granular soil specimen gradually being wetted starting from its bottom. The wetting or saturating of the collapsible soil simulates the transient unsaturated-saturated water flow during a gradual rise in groundwater table or during the first reservior filling of an embankment dam.

A modified triaxial apparatus was employed in the program. The major modification includes the ability to measure pore-air and pore-water pressure in the specimen, separately. Fig.1 shows the description of parts of the modified triaxial apparatus.

3.1 The Specimen Used

The sample prepared in the research study is soil derived from soil used in construction of 'Matsutani' dam, Japan. The soil is hand-washed (to make it free from clayey substance), sieved andblended to form granular soils (soil type 1, soil type 2 and gravel soil in Table 1) having approximately the same uniformity coefficent.

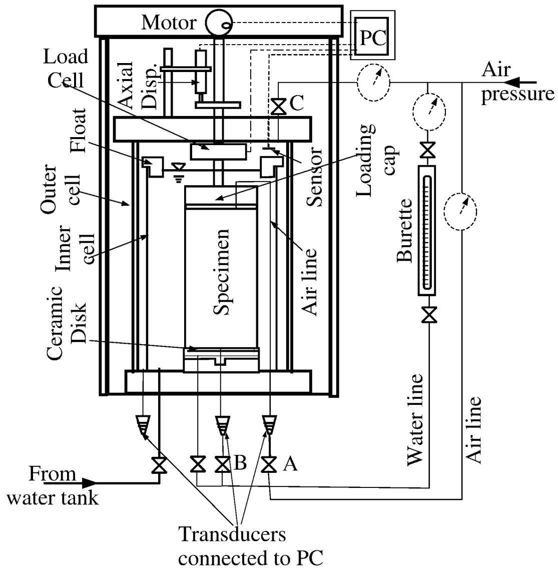

Fig. 1 The modified triaxial apparatus.

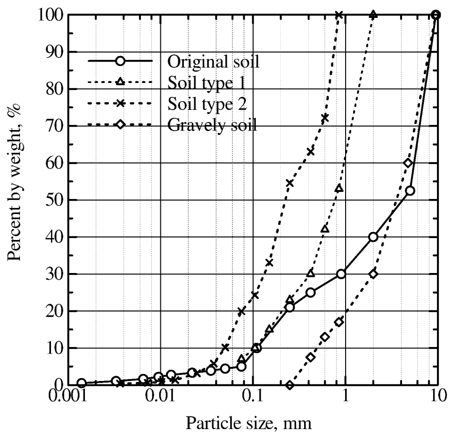

Fig. 2 Particle size distribution curve

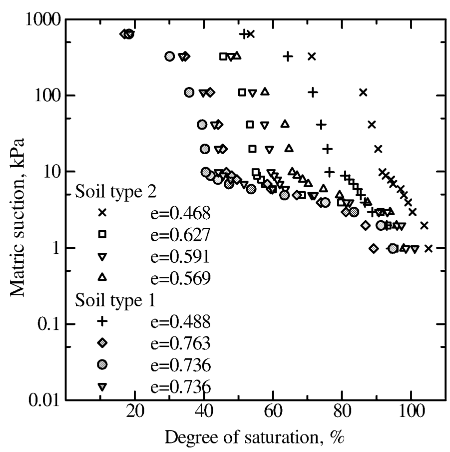

Fig. 3 Soil water characteristic curve of compacted granular soil

Table 1 Physical properties of soil used

Index test	Soil type 1	Soil type 2	Gravel soil
Standard compaction tests			
Maximum dry density (g/cm^3)	1.79	2.02	
Optimum water content (%)	14.2	12.3	
Grain size distribution			
Percentage of gravel (%)			75
Percentage of sand (%)	90	80	25
Percentage of silt (%)	7	20	
Specific gravity (g/cm^3)	2.73	2.76	2.87
Maximum void ratio	1.02	0.94	
Minimum void ratio	0.52	0.32	
D_{10} (mm)	0.10	0.05	0.45
D_{30} (mm)	0.32	0.15	2.0
D_{60} (mm)	1.0	0.42	5.0

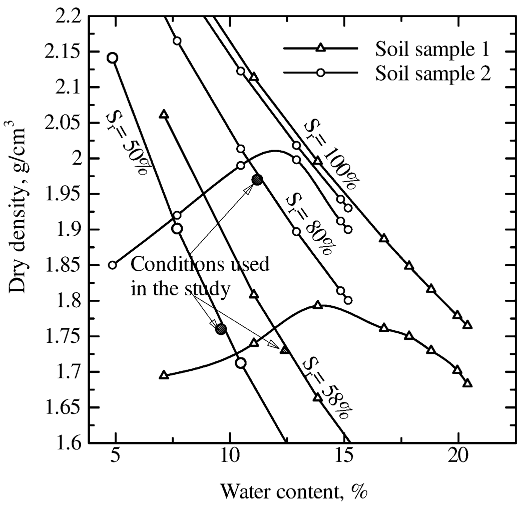

Fig. 4 Compaction curves of the soil used

The grain size distribution of the blended sample together with the original soil can be shown in Fig.2 and the soil index properties of these soils are summarized in Table 1. The soil water characteristic curves of the samples, determined by suction method with a capacity of 1000kPa, are shown in Fig.3 Specimens from each blended soil at the dry-of-optimum water content and lower dry unit weight, which is the practice of most engineering structures made of soil during construction, were prepared. These conditions usually result in meta-stable structure which leads to collapsible soil.

The specimens were compacted in the compaction mold of 150mm in diameter and 100mm in height (but large sized granular soil is tammed on the triaxial apparatus). Fig.4 shows the compaction curves obtained and the initial conditions of some specimens.

3.2 The Test Procedure

The compacted specimen is sandwiched between a high air entry (200kPa) ceramic disk at the bottom and nonwoven fiber filter, which is glued to the loading cap, with water entry value of 100kPa, at the top of the specimen. The air pressure, water pressure and confining pressure are applied to the specimen through valve A, B and C respectively (see Fig.1).

After assembling the apparatus the desired matric suction in the specimen was obtained by controlling the pore-air and pore-water pressures using the axis-translation technique (Fredlund *et al.* 1993; Hilf 1956).

The specimens were then left for equilibration of the pore-air and pore-water pressure within the entire length. Thereafter, the specimens were subjected to different magnitude of isotropic compression at constant applied suction. After compression, the matric suction in the soil is reduced by increasing the water pressure, in doing so water will gradually enters the specimen from the bottom through the high air entry ceramic disk. Both pore-air and pore-water pressure at the specimen boundary is controlled to bring the boundary suction to zero during wetting process.

4. Results and Discussions

From the experiment performed on different specimens it is found that all speciemens show settlement due to wetting. Fig.5 shows the experimental result of volume change behavior of all phases, (total, water, and air phase), of the soil specimen for different initial conditions. The total volume change and the amount of water that inters into the soil specimens are measured values, whereas, air phase volume change is calculated from the principle of conservation of mass.

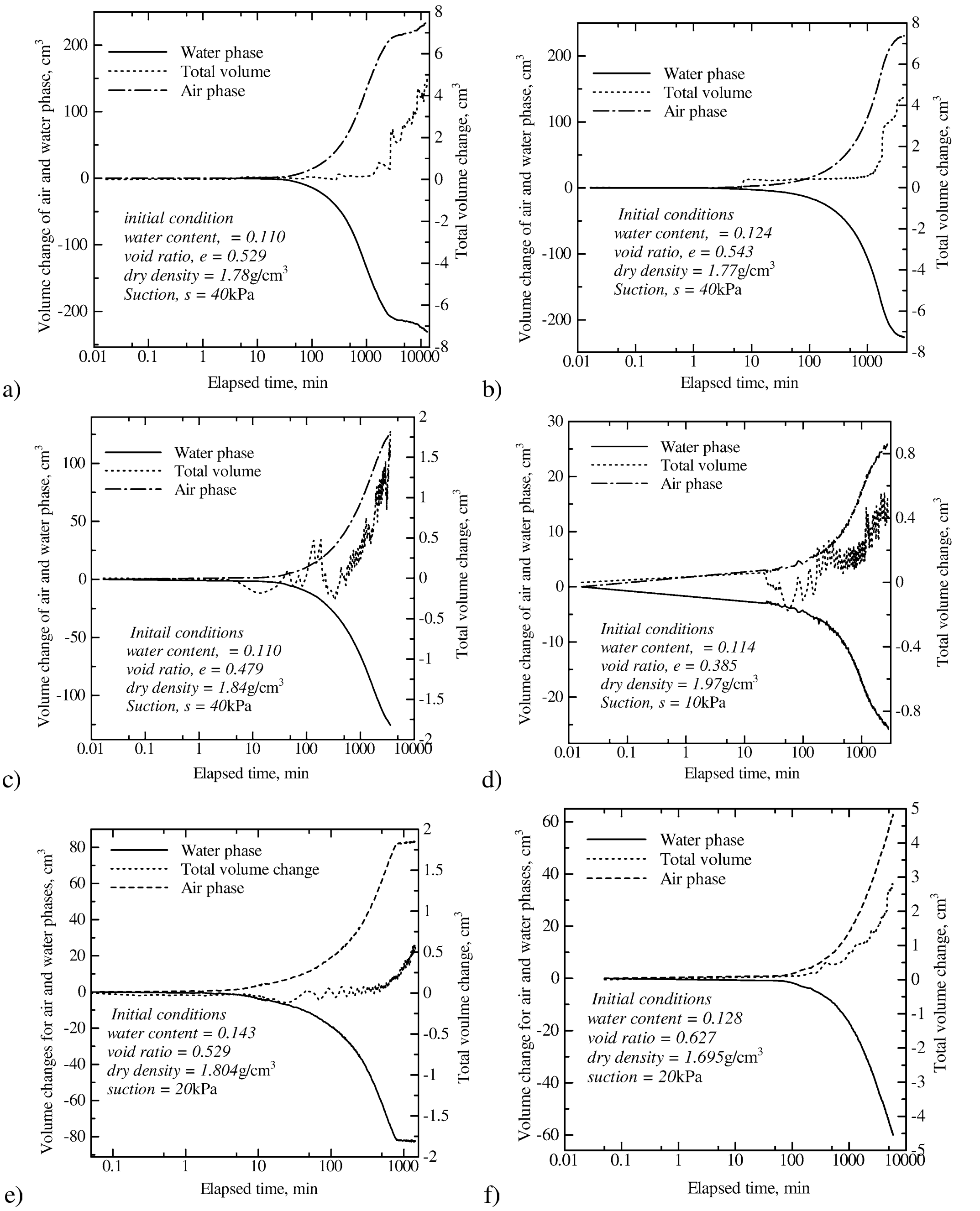

Fig. 5 The volume change during suction history for different initial conditions

In all specimens we can see that there is a reduction in total volume as the matric suction of the soil reduces, or as the water enters the specimen. However, the magnitude of volume change due to suction reduction for the same type of soil specimen is seen to be the function of the initial condition of the specimen.

Comparing Fig.5 a) and b) we can see that for the same applied initial matric suction and same dry density the specimen with smaller water content undergoes more volume reduction under wetting. Specimen having higher initial matric suction deform more during wetting, compare Fig.5 b) and f). In addition specimen with dry density close to its maximum dry density (See Fig.5d) induces the minimum volume change on wetting. Specimen initially compacted to the wet side of optimum water content (Fig.5e) undergoes very small volume reduction on further wetting, evenif it has lower dry density.

Figs.6a)~f) show the experimental results of change in void ratio and degree of saturation during wetting process on soil specimens prepared at different initial conditions.

All the result data are summarized in Table 2, including collapse potential and its initial soil properties (The collapse potential is defined as volumetric strain or the ratio of void ratio change to initial specific volume = $\frac{de}{1+e} \times 100\%$)

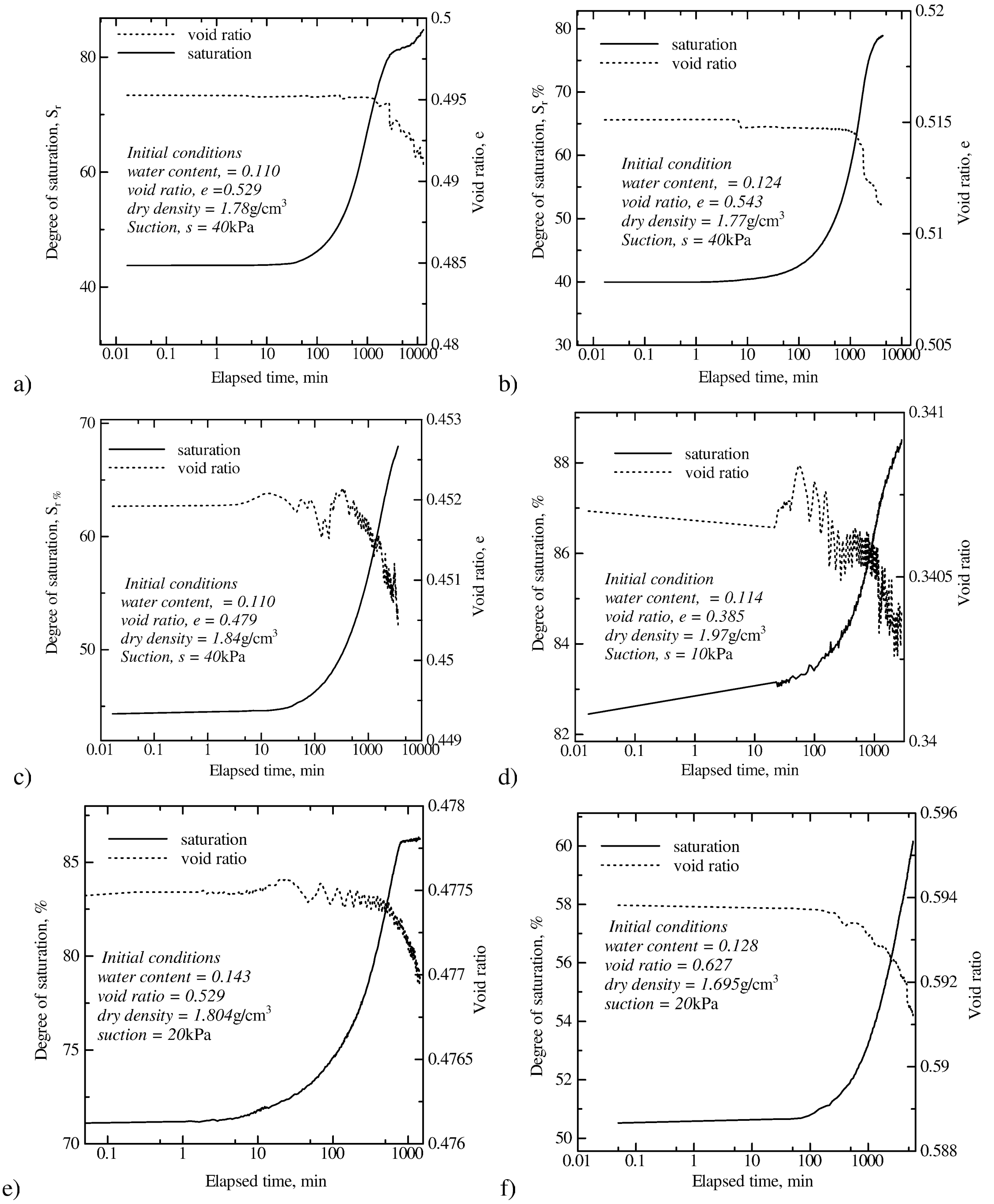

Fig. 6 The soil mass properties during suction history

In all the results presented in Figs.6 we can clearly observe that the volume reduction of the soil commences after a certain quantity of water enters the specimen, or after the degree of saturation reaches a certain critical value. This state at which wetting-induced volume reduction commences is strongly believed to be related to the air entry suction of the soil. As can be observed in these figures all specimens didn't reach full saturation, however, show wetting-induced volume reduction. Therefore, partial wetting test can also show typical volume change behavior of unsaturated soil with respect to suction change.

The above data were presented from the experimental result undertaken by reducing all the applied matric suction to zero at once, and measuring the volume change of the soil through time, in a sense it was difficult to talk about the relationship between the history of matric suction reduction to the response of total volume change of the specimen. Hence further experimental investigation was undertaken through reducing the applied matric suction stepwisely.

Specimens, at their initial condition and applied initial matric suction of 80kPa, was isotropically loaded under a previously specified net confining pressure, $(\sigma_3 - u_a)$, of 200kPa. Both pore-air and pore-water pressures were controlled in a drained mode.

Table 2 Summary of the experimental results.

Soil types	Graph names in Fig.5	Initial water content	Initial dry density g/cm^3	Inital void ratio	Matric suction (kPa)	Cell pressure (kPa)	void ratio before wetting	void ratio after collapse	collapse potential (%)
1	a)	0.110	1.786	0.529	40	100	0.495	0.491	0.268
1	b)	0.124	1.769	0.543	40	100	0.515	0.511	0.264
1	f)	0.128	1.695	0.627	20	100	0.594	0.591	0.188
2	c)	0.110	1.843	0.479	40	100	0.452	0.449	0.207
2	d)	0.114	1.974	0.385	10	150	0.341	0.340	0.075
2	e)	0.143	1.804	0.529	20	150	0.478	0.477	0.068

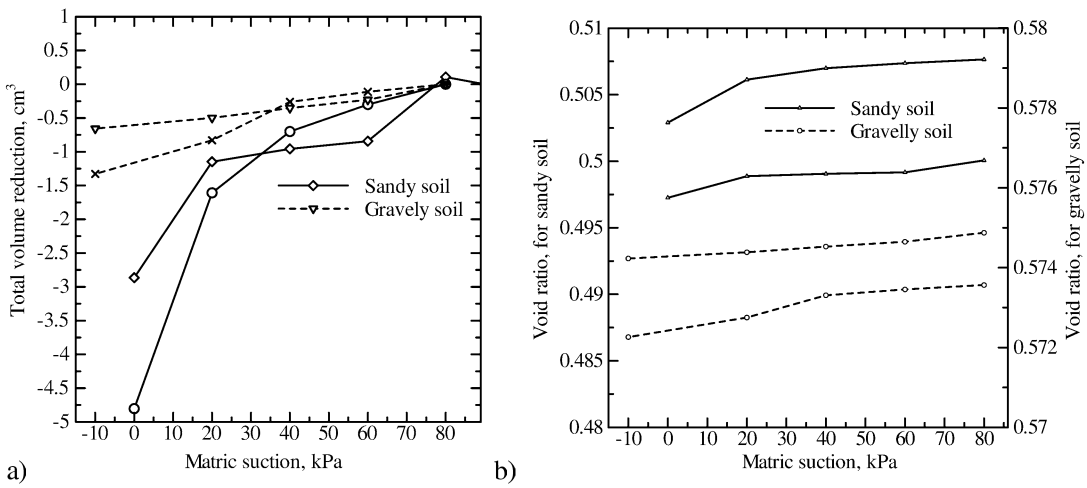

Fig. 7 Collapse for two type of soils, a) total volume reduction, b) change in void ratio on wetting.

Specimens were allowed to consolidate at various steps of decreasing matric suction (i.e., following wetting path) until saturation was reached. The applied net confining pressure was maintained constant throughout the test. The test started by applying a matric suction of 60kPa. This was the first step toward saturation (collapse). The changes in total volume of the specimens were monitored during each step of the tests. The net inflow of water to the specimen also was monitored to determine the change in degree of saturation.

The specimens were allowed to equilibrate at matric suction equal to 60, 40, 20, 0kPa to better define the collapse behavor of the soil.The equilibration time is about 3~4days for every applied matric suction.

However, the sample didn't reach complete saturation at zero value of applied matric suction, even after applying back pressure of circa 10kPa, this behavior suggests the need for longer time of equilibration at every suction step. However the general trend of volume change induced during suction reduction can be observed clearly, except for lack of the total amount of volume change of the soil as the entire specimen approaches saturation or zero matric suction.

Figs.7a) and b) show the total volume change and void ratio changes during wetting versus matric suction for all specimens under different initial conditions. The result is summarized in Table 3.

Three distinct phases in the collapse mechanism, as discussed by Jose *et al.* 2000, were expected, however, only two phases were observed in this result. In the first phase called *'pre-collapse phase'*, at relatively high matric suction, the soil doesn't collapse and only small deformation occurs in response to a decrease in matric suction. In the second phase *'collapse phase'*, at actually intermediate matric suctions large deformations are observed in response to a decrease in matric suction.

The third phase, *'post-collapse phase'*, would be an absence of deformation at lower matric suctions as the matric suction of the entire specimen is reduced to zero. However, bringing the entire specimen to zero matric suction seems time-consuming and uneconomical, since the size of the specimen is large compared to the usual specimen size and the permeability of ceramic disc is in the order of 10^{-9} cm/s from which one can guess the time that is needed to saturate the whole specimen.

Table 3 Summary of step-wise experimental results

Soil	Before wetting				After wetting		Collapse potential
— type	s (kPa)	$w(\%)$	$\gamma_d(\text{g/cm}^3)$	e	$w(\%)$	e	$\Delta e/(1+e_0)$
Sandy	80	7.6	1.75	0.508	7.8	0.503	0.332%
soil	80	6.6	1.75	0.500	6.8	0.497	0.200%
Gravely	80	3.9	1.69	0.575	4.3	0.574	0.063%
soil	80	4.0	1.69	0.574	4.3	0.572	0.127%

Also shown in these figures is the influence of soil type (grain size) on the volume change behavior induced by reduction in matric suction. For the same applied confining stress and initial matric suction, soil which possesses more fine grain induced more volumetric reduction than coarse-grained soil.

This implies that if a soil possesses more fine grain it will result in the formation of meta-stable structure which leades to more wetting-induced settlement and collapse.

5. Collapse Mechanism and its Potential

It is believed by most geotechnical researchers that collapse mechanism differ considerably from the classical consolidation process. In the consolidation process, the total volume change of the saturated soils occur as a transient process. Collapse, on the other hand, appears to occur in a relatively short period time in response to the infiltration of water in to the soil at a constant vertical stress.

However within the framework of the present test performed on triaxial apparatus, it appears that there is no as such sudden reduction in volume as the water enters the specimen. However, a continous wetting-induced settlement as water infiltrate from bottom to upward, and settlement appears to occur in a relatively longer period of time as opposed to what is believed.

As already mentioned in the previous section, for the soil to experience wetting-induced volume reduction, four factors are said to be needed, such as; unsaturated fabric, applied stress, cementing agent and addition of water. However from this experimental investigation we have found that the need for cementing agent (like clay mineral) is found to have less effect, since the specimen is prepared hand-washed granular material. Therefore, we can say that for a soil to undergo volume reduction on wetting only three factors are believed to be needed in this experiment:

- An open partially unstable, unsaturated fabric
- A high enough net total stress that will cause the structure to be meta-stable, and
- The addition of water to the soil, which causes the suction to reduce and the unsaturated fabric or the inter-aggregate contact to fail in shear, resulting in a reduction in total volume of the soil mass.

The dry density, the initial water content and the percent fine are shown to be the most important influential factors of soil properties when we investigate the collapse behavior and collapse potential of compacted/unsaturated soil. An inverse relationship between the initial soil properties and the percent collapse (collapse potential),is pertinent. The collapse potential decreases with an increase in the initial water content or dry density. The results are in general agreement with the observation made by Tedapelli *et al.* 1992.

6. Conclusions

Generally, the following conclusions are drawn from the investigation conducted on granular specimens subjected to wetting stress path.

- At a given net confining pressure and following a wetting stress path, collapsible soils believed to follow three distinct phases in terms of total deformation with a decrease in matric suction: the “pre-collapse”, the “collapse” and the ”post-collapse phase”.
- The dry density and initial water content are shown to be the most important influential factors of soil properties when we investigate the collapse behavior of compacted soil. Generally an inverse relationship between the initial soil properties and the percent collapse is pertinent.
- For soil to undergo collapse the existence of cementing or bonding agent is found to be not the necessary factor as believed by many researchers. However, an agreement can be reached from the understanding that the matric suction of the soil (capillary force) can be considered as a cementing agent that stabilizes the soil to remain in unsaturated condition carrying the external pressure acting upon the soil and that bring the soil to a meta-stable state. The strength of sandcastle could be a good example for the effect of matric suction on granular soil.

- Estimated collapse settlement based on full-wetting collapse potential may not be realized for many field condtions. In fact, it is extremely uncommon that complete saturation to the full depth of the collapsible soil deposit occurs, unless wetting is by slowly rising groundwater, which definitely took long time. This fact must be taken into account during estimation of collapse settlement and in assessing the magnitude of the "calculated risk".

- When we talk of collapse due to wetting, it doesn't necessarily mean full depth wetting and sudden deformation of the soil mass. From the experimental investigation undertaken, it is found that the collapse of a soil is associated with localized shear failure (due to partial wetting) rather than an overall shear failure of the soil mass.

- Collapse, in the framework of the present laboratory testing technique, can be defined as a consolidation/compression of soil mass due to gradual increase in pore-water pressure (from bottom to upward), through time. It is different from the real consolidation process in that, during consolidation volume change occur due to dissipation of excess pore-water pressure. Otherwise, when one talk about volume change behavior of soil during wetting process one has to deferentiate collapse from wetting-induced settlement in that collapse is a sudden volume change phenomenon which occur in a short time frame, whereas, wetting-induced settlement is a transient process, similar to consolidation process, that depend mostly on the permeability and/or the rate of flow of water into the specimen.

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不飽和粒状土のコラプスポテンシャルとそのメカニズム

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要 旨

コラプスを示す土は含水比に敏感で湿潤過程には体積圧縮挙動を示す．荷重作用下で湿潤する場合に締固められた土がもつコラプスポテンシャルは土木工学応用における一つの主要な関心事である．湿潤によって締固めた土が示す体積変化挙動の研究は，不飽和地盤工学において注目される最近の一トピックである．本稿では締固められた粒状土について実験的にその力学挙動を分析した結果を述べる．体積変化挙動は各種応力状態について独立に制御できる改良した三軸試験装置を用いて観測した．湿潤過程の応力径路は，コラプス性の土供試体が等方応力負荷状態で地下水位が上昇する現場を想定して選択された．全体積変化及び含水比変化を観測した．実験データから，初期状態の異なる不飽和粒状土のコラプスポテンシャルとそのメカニズムについて分析した．

キーワード: コラプス，湿潤径路，改良型三軸セル，マトリックサクション，粒状土