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Effect of stress state and particle-size distribution on the stress reduction of sandy soils during saturation

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HIGHLIGHTS

- Triaxial test was conducted on dry, saturated and dry samples followed by saturation.
- Effects of relative density, stress, previous loading and unloading and gradation curve were studied.
- The more stress applied on the samples, the more stress release was observed due to saturation.
- Uniformly graded specimens were more prone to collapse than well-graded samples.
- With the same uniformity coefficient, soil collapsibility decreases as the maximum particle size increases.

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ABSTRACT

In this study, stress reduction due to saturation of sandy soils is investigated via conventional triaxial shear strength apparatus. Triaxial tests were performed on dry samples, saturated samples and initially dry samples followed by saturation during shearing. Effects of stress states, initial loading and unloading and particle-size distribution (PSD) curve were studied on the behaviour of the samples. It was observed that the amount of stress reduction increases by the decrease in the relative density and the increase in the confining pressure and the shear stress level during saturation. With the same uniformity coefficient, the coefficient of stress recovery increases as the maximum particle size increases, results in less collapse in sandy soils.

1. Introduction

A sudden reduction in the volume of a dry soil mass upon wetting leads to collapse settlement in the mass. This sudden settlement due to wetting occurs without any change in the applied load and only because of wetting. In reality both stress state and deformation field of a soil mass changes due to saturation, which are of paramount importance especially in loose sandy soils or where an important function is expected from the soil, e.g. in a filter zone of embankment dams. In the design of zoned embankment dams, the filter material is used to prevent erosion of the clay core and to be a transitional zone between clay material and gravelly material either downstream or upstream. As this zone is a protective layer against piping failure in clay core, its properties are important especially in the first impoundment of the reservoir. If the filter zone is compacted below a specific limit, or if enough water is not applied during compaction, filter zone may experience sudden collapse in the first impoundment, resulting in large deformation and even failure in this zone. If too much effort is applied in its compaction, due to an increase in its stiffness the absorbed stress from the dam body increases in the filter zone, which causes the filter material to become more brittle and prone to collapse.

Geotechnical investigations with laboratory tests and field monitoring have indicated the possibility of stress reduction and collapse settlement in a wide range of geological materials. This has been extensively investigated by many researchers, for example Nobari and Duncan [1]; Egretli and Singh [2]; Sivakumar and Wheeler [3]; Rao and Revanasiddappa [4]; Jotisankasa et al. [5]; Alonso and Cardoso [6]; Mahinroosta et al. [7]. Factors needed to produce collapse and stress reduction in a soil mass [8] are an open, partially unstable and unsaturated fabric in the soil mass,

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high enough net total stress to cause the structure to become unstable, a bonding or cementing agent that stabilizes the soil in an unsaturated condition, and finally the addition of water to the soil which causes the bonding or cementing agent to be reduced and the inter-aggregate or inter-granular contacts to fail in shear, resulting in a reduction in total volume of the soil mass. One of the most important features of water in this process is that it flows into the soil and causes particles to slip over each other more easily [9].

In general, three reasons can be identified as being responsible for the collapse settlement due to saturation: 1) sudden reduction in confining pressure, 2) easier sliding of particles because of the lubricating effect of water, and 3) particle breakage due to the interaction of water and surficial micro-cracks (if any) of the particles [9]. Several factors are responsible for the amount of individual particle breakage, including stress level, stress path, particle size, relative density, particle shapes, mineral hardness, and water presence [10]. The effect of moisture content, cyclic wetting and drying, matric suction, geological origin, particle shape and fine contents have been studied in different research, for example Rao and Revanasiddappa [11], Huat et al. [12], Yang and Wei [13], Bruchon et al. [14] and Brink and van Rooy [15]. Due to the particular focus of this study, literature related to soil stress state and PSD curves are discussed below.

Lee et al. [16] described the effect of wetting on the strength and volume change characteristics of clean sands, determined from drained triaxial compression tests. They concluded that additional crushing upon wetting was a major factor contributing to the observed difference in the strength and volume change characteristics of the wet and dry samples. Stanculescu [17] performed a number of triaxial tests on dry samples followed by wetting, in which specimens were subjected to various values of stress difference and confining pressure; the results of these tests indicated that the amount of collapse volume change due to wetting increases as the value of shear stress and confining pressure increase. Zur [18] described triaxial tests on specimens which had been consolidated at various values of principle stress ratio ($\sigma1/\sigma3$). As in the tests performed by Stanculescu, those performed by Zur showed that the amount of compression due to wetting increases as the confining pressure increases.

Nobari and Duncan [1] performed a number of 1-D compression tests on a portion of the Pyramid dam material, which was finer than the No. 4 sieve, to investigate the effect of submergence on the compressibility of granular soils. The results of these tests showed that the amount of compression induced by wetting decreased by increasing the relative density and initial moisture content. As a result of wetting, the rate of volume compression increased and eventually approached the volume change curve of the initially wet specimen.

In the study conducted by Naderian and Williams [19], the effect of normal stress was evaluated on the collapse phenomenon using claystone and sandstone samples. With performing a number of compression tests they found that the amount of collapse settlement increases as the applied stress increases. Alawaji [20] carried out sets of oedometer and direct shear test on loess soils in which the initial dry density and the normal pressure at the wetting and shearing process were each varied in turn. Oedometer results indicate that collapse potential (the change in volumetric strain due to inundation under constant normal pressure) decreases with density and increases logarithmically with normal pressure.

Silvani et al. [21] investigated the effects of buoyancy forces and the decrease in the coefficient of friction in a rockfill column. Their simulation highlighted the occurrence of a significant rearrangement in rockfill material during the saturation. Mahinroosta and Oshtaghi [22] investigated the collapse behaviour of clean gravels and clean sand via a medium-scale direct shear test. They found that an increase in vertical stress level and shear stress level results in more collapse settlement and more stress reduction during saturation. It was shown that the collapse potential in sand samples was much higher than gravelly material with the same relative densities. In fact, particle rearrangement and particle breakage were the fundamental cause of the collapse in sandy soils and gravelly soils, respectively. In discovering the importance of the input data from an artificial neural network, Hasanzadehshooiili et al. [23] showed that sand content and normal stress applied to specimens were the most effective parameters to predict collapse settlement of soil samples. The effect of stress condition on collapse behaviour of a rockfill material was also investigated by Heshmati et al. [24]. They found that stress release due to collapse of the material increases with confining pressure.

In high embankment dams, different points inside the filter zone experience unique stress history during construction, initial impoundment and operation. Fluctuation of water in the upstream shell also changes the stress state upon the filter zone, resulting in different confining pressure and stress level. Although the effect of confining pressure and shear stress on the collapse of soil samples has been studied by several researchers as mentioned above, the effect of previous stress history on the stress reduction has not been taken into account in the literature. Therefore the first part of this study is to investigate the effect of stress state and its previous stress history on the stress reduction of sand samples. An equation is introduced to relate the amount of stress release to confining pressure and shear stress level, which can be applied in numerical modelling of soil deposits to predict the amount of collapse settlement due to saturation [25].

The effects of PSD curve on the shear strength of granular material were studied by different researchers, for example Anagnosti and Popovic [26]; Marachi et al. [27]; Marsal [28]; Anagnosti and Popovic [26]; Li [29]. Generally, it could be expected that a poorly-graded granular material (low uniformity coefficient) would have a higher strength than a well-graded granular material, assuming a constant relative density for both. However, when samples are compacted to their maximum density, the increase in uniformity coefficient may result in higher shear strength [26]. Particle size also has an important role on the strength of soil samples; it is generally accepted that shear strength of soil samples with large particle size increases with the particle size ([28,30]). However, some research showed no effect or an opposite effect [31]. Increasing the coarse fraction in soil samples increases the constant volume friction angle of the soil mixtures of fine and natural coarse fraction [29]. As can be seen, the effect of particle size and uniformity coefficient on the shear strength of geo-materials were studied by several researchers, but their effect on the stress reduction of sands during saturation were not observed. This is especially apparent in sands in the range of the filter zone of embankment dams, where they may exhibit high confining pressure and shear stress levels during dam operation. Therefore, the effects of PSD curve on the stress reduction of sandy soil is another component of this study.

When a soil mass is subjected to wetting, both stress state and deformation field will change; there will be a sudden reduction in the stress values followed by a volumetric change. In conventional triaxial test apparatus in this study, the stress change during saturation of the samples was determined directly from the reaction of the load measuring ring; however measuring the volumetric deformation and matric suction of the initially dry samples during saturation were not possible. For instance, changes in the stress level due to saturation is studied in this paper as an indicator of collapse in the sand samples.

In this study, preliminary tests were conducted to determine physical properties of the selected sandy soils, then shear strength