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Effect of cyclic loading on the response of an unsaturated railway embankment

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Abstract

A good quality coarse-grained soil with minimum fines is the most important requirement for the railway embankment to exhibit minimum deformation during its design life. The soil in the railway embankment undergoes long-term cyclic loading and changes in the water content during its lifetime. To understand the performance of the embankment, this study investigates the mechanical behaviour of coarse-grained soils in terms of accumulated axial strain and volumetric changes during cyclic loading in unsaturated conditions. Suction-controlled unsaturated drained cyclic loading tests were carried out for the soils compacted at different degrees of saturation. The initial suction is measured immediately after the compaction and is deeply investigated with the changes in the degree of saturation. The results show that the decrease in the degree of saturation decreases the accumulated axial strain substantially, at the same degree of compaction. The initial suction is the parameter that resists the particle rearrangement during the cyclic loading. The larger the initial suction, the accumulated axial strain is lower. In addition to that, the larger the initial suction, the volumetric strain shows a more contractive behaviour. This result shows that minimal changes in the initial suction and the degree of saturation could affect the deformation behaviour of soils during cyclic loading.
Keywords: Unsaturated soil, Cyclic loading, Accumulated axial strain, Initial suction.

1 Introduction

Many studies revealed that the mechanical behavior of the railway structure under the cyclic vehicle loading is generally referred to the permanent axial deformation[1]. The cyclic loading simulates the vehicle loads, which change in direction and amplitude. So, it's necessary to understand the deformation behavior of the soils during cyclic loading. Large-scale cyclic triaxial tests have been performed for the upper part of the interlayer in the railway embankments [2, 3]. The results showed that the water and fines contents significantly influenced the axial deformation. Also, the specimens with more water content and increased fine content exhibited a larger permanent deformation in the saturated condition. Zhong He [4] also discussed the deformation behavior of coarse-grained soil by conducting the numerical dynamic triaxial tests in unsaturated conditions and concluded that the permanent axial strain has increased with the increase in water content around the optimum water content condition. Wang [5] investigated the dynamic response of the lower part of the interlayer soil under cyclic loading (1900 cycles) and the loading amplitudes (around 200 kPa) was high than the common value. However, Wang [1] also mentioned that permanent deformation behavior is more complicated when dealing with the fine-grained soils as the effect of suction increases with fine content. Furthermore, previous studies reveal that they did not deal with the correlation between the suction and permanent axial strain. In addition, the experimental studies are very limited in understanding the deformation behavior and the water retention behavior during cyclic loading.

Hence, a dedicated series of suction-controlled cyclic loading testing is performed on the coarse-grained soil under unsaturated drained conditions to address the above shortcomings. The deformation behavior in accumulated axial strain is investigated by cyclic triaxial testing with many loading cycles (10,000 load cycles) with varying degrees of saturation. Additionally, the effect of initial suction and the correlation between the initial suction and deformation properties were discussed. The results will provide a clear understanding of the effect of the degree of saturation along with the initial suction on the deformation behavior of soil during cyclic loading.

2 Methods

2.1. Materials

The Inagi sand is the coarse-grained soil containing fines of around 4.75% which is considered a good quality of soil for the railway embankment. The maximum dry density ($\rho_{d,\ max}$) and optimum water content (w_{opt}) are 16.57 kN/m3 and 18.5% respectively, obtained from the standard proctor test of 1.0 following the JGS 0711-2009 method. The optimum degree of saturation ($S_{r,\ opt}$) is around 86.5%. The specific gravity of WFS particles was found to be 2.65. The uniformity coefficient (U_c) and coefficient of curvature (U_c’) were equal to 0.96 and 2.38, respectively. The particle size distribution curve for the soil is shown in Figure.1.

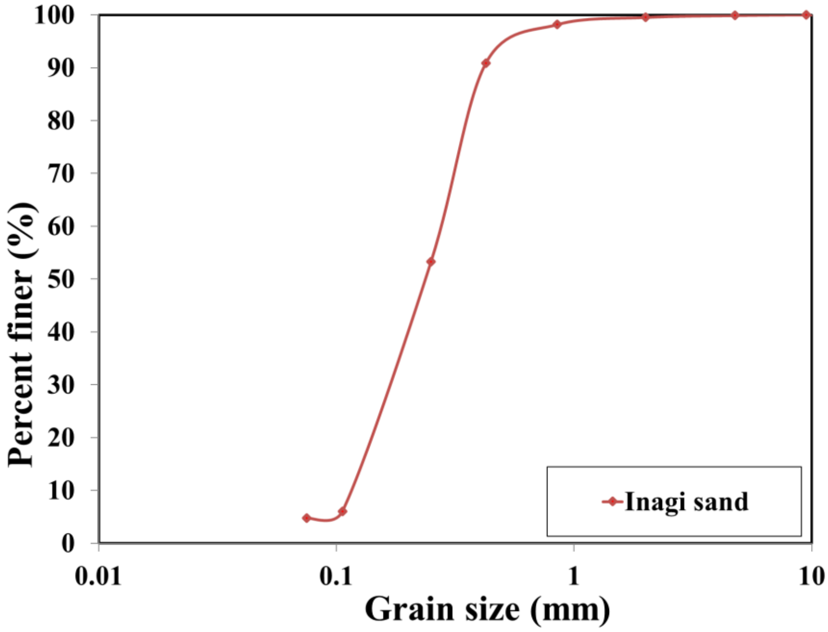

Figure 1: Particle size distribution curve for Inagi sand.

2.2. Experimental Set-up

A special apparatus called linkage double cell triaxial apparatus is used (Figure. 2) to study the deformation behavior of unsaturated soil. This apparatus can externally control pore air pressure (u_a) and pore water pressure (u_w) to maintain suction during cyclic loading. An external positive pressure supply should be connected at the top cap and bottom pedestal to control u_a and u_w, respectively, and thus maintain the suction. With this specialized arrangement, the suction was maintained as the initial suction in all the tests conducted under drained conditions. The initial suction is the suction calculated from the measured u_a and u_w in the sample just immediately after the compaction and which is before the cyclic loading. A hydrophobic filter was attached to the top cap, which prevented water flow and measured air pressure with the help of u_a transducer. At the bottom pedestal, a membrane filter was attached, which prevented airflow and measured water pressure using a pore water pressure transducer. The membrane filter is saturated before installing on the porous stone of the bottom pedestal (Figure. 2.) and the details can be found [5].

The volume change during cyclic loading is measured with the help of a double cell system which could measure the overall changes in the specimen. On the other hand, the volumetric strain caused by drained pore water is measured using the differential pressure transducer (DPT) for noting the changes in water level in the burette connected to the sample. The variation in Volumetric strain (%) caused by drained water is defined as the ratio of the amount of water drained/absorbed to the volume of the soil specimen just before the water is drained/absorbed.

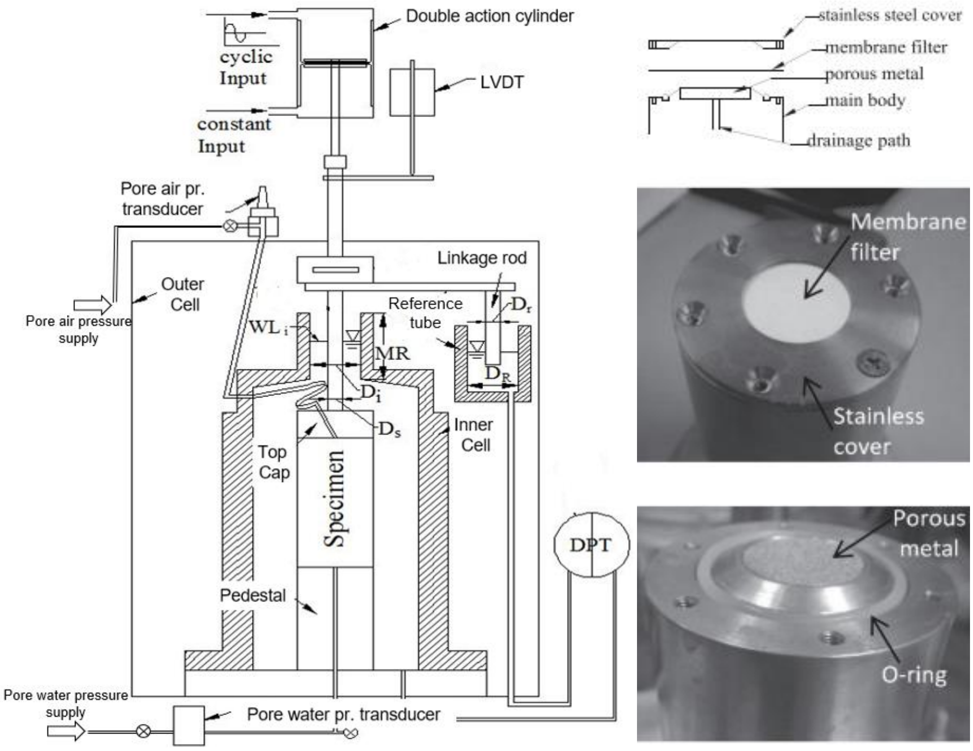

Figure 2: Linkage double cell triaxial apparatus with ability to control and measure suction (modified from *H. Wang et al., 2017*).

3 Results

A series of suction-controlled drained tests were conducted by varying the degree of saturation (S_r) at the same degree of compaction (D_c) in unsaturated conditions, controlling the initial suction with a high-frequency cyclic loading of 1 Hz at a confining pressure of 50 kPa under the Cyclic stress ratio (CSR) value of 0.26 The soil specimens with a diameter of 50mm and height of 100mm were prepared using the moist tamping by the under-compaction technique.

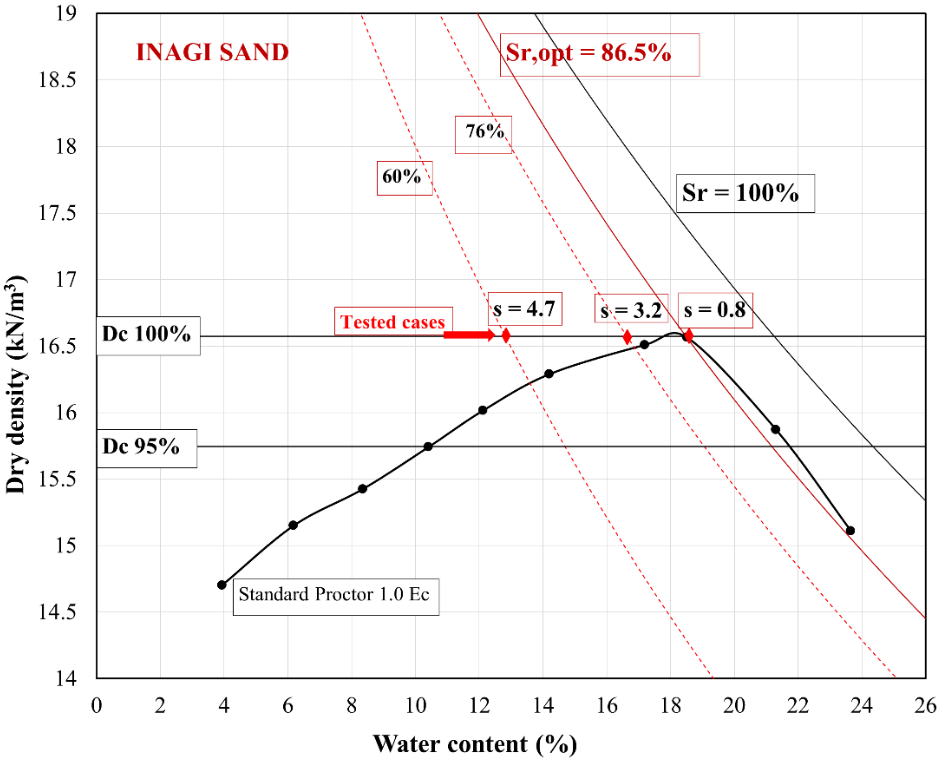

Figure 3: Tested compacted states with the initial suction (s) values in kPa shown on compaction curve of Inagi sand.

3.1. Effect of initial suction on degree of saturation

The initial suction values obtained at 100% D_c are 4.7 kPa, 3.2 kPa and 0.8 kPa for S_r = 60%, Sr= 76% and S_r = 86.5% respectively. This decreasing suction with the increase in S_r implies the change in the microstructure from coherent to dispersive with the increase in S_r.

3.2. Effect of degree of saturation (S_r) on accumulated axial strain and volumetric strain

In all tested cases, the accumulated axial strain of the specimen increases rapidly during the initial stage of cyclic loading reaching around 80% of the total accumulated axial strain. After that instance, the rate of increase in deformation slows down with the loading cycles.

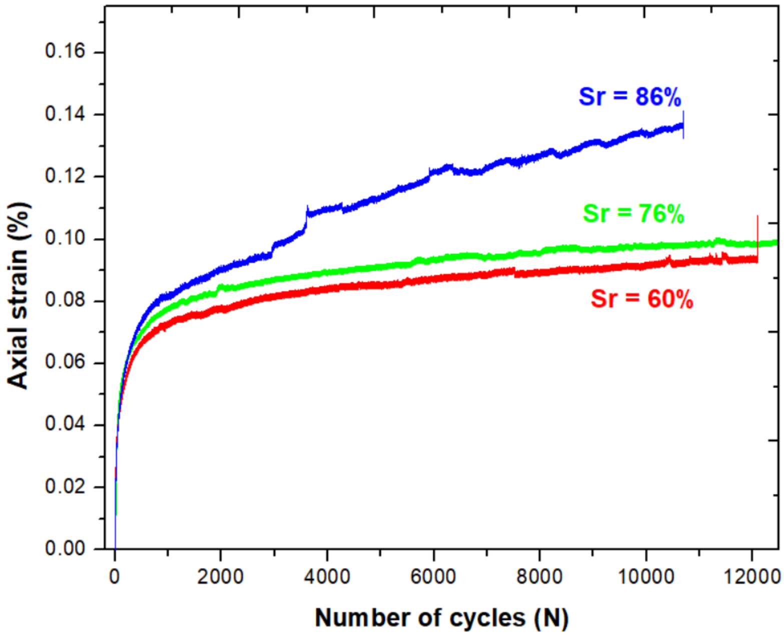

Figure 4: Variation of accumulated axial strain with the changes in degree of saturation at degree of compaction D_c= 100%.

It is observed that the soil compacted at S_r = 60% exhibits the lowest strain accumulation (Figure 4) when compared to the soil compacted at $S_{r,\, opt}$. However, showing more contractive volumetric behavior (Figure 5). This is because the soil specimen compacted at less water content (high suction) possesses more meniscus water when compared to the high-water content (low suction) [6]. The higher meniscus water induces a greater bonding effect and higher suction which leads to less particle rearrangement in terms of axial strain and in turn shows the significant volumetric strain.

At low S_r, the movement of pore water from the sample is increased because of the presence of more meniscus water and whereas, at high S_r, there is less or no movement of pore water. In addition to that, the increase in S_r, the soil structure changes from coherent to dispersive microstructure in which the pore size decreases and hence, the water-retaining capacity increases.

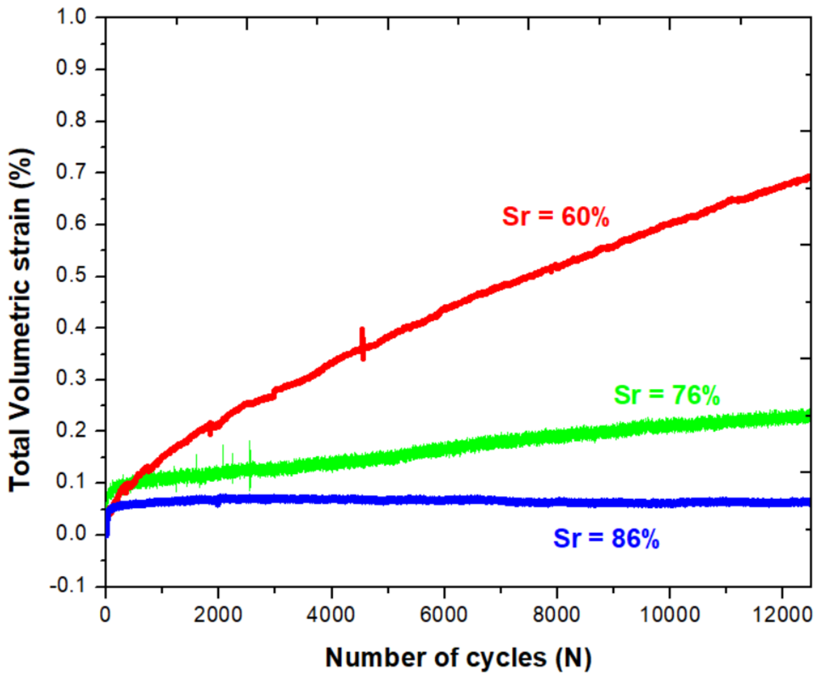

Figure 5: Variation in the total volumetric strain with the changes in degree of saturation at degree of compaction D_c= 100%.

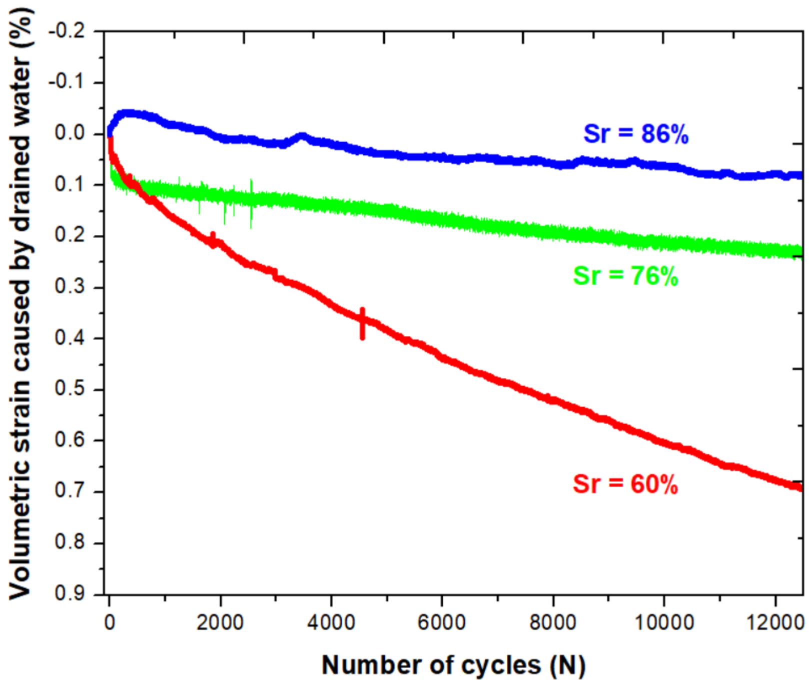

Figure 6: Variation in volumetric strain caused by drained water with the changes in degree of saturation at degree of compaction D_c= 100%.

4 Conclusions and Contributions

This paper presents the understanding of the soil mechanical behavior under cyclic loading. Suction-controlled unsaturated drained cyclic triaxial tests were carried out while the changes in the degree of saturation (S_r) were monitored continuously. It was observed that the accumulated axial strain increases rapidly during the initial loading cycles, reaching around 80% of the final accumulated axial strain. The decrease in the degree of saturation (S_r) shows the decrement in accumulated axial strain. This is because the increase in initial suction with a decrease in the degree of saturation had a large impact on resisting the particle rearrangement during repeated cyclic vehicle loading. The larger the initial suction, the accumulated axial strain is lower. In addition to that, the larger the initial suction, the volumetric strain shows a more contractive behavior. This means with the decrease in the degree of saturation, the soil shows more contractive volumetric strain behavior. This is because the movement of the pore water from the sample is increased with the decrease in the degree of saturation (S_r). It can also be noted that the soils compacted at a high degree of saturation shows almost dilative behavior and less or no pore water movement. This result exhibits that very small changes in the initial suction could affect the deformation behavior of soils during cyclic loading. Such a kind of understanding soil behavior during cyclic loading is important for the railway embankment to achieve high performance.

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