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Compression characteristics of compacted sand-bentonite mixtures with and without saturation

Caractéristiques de compression des mélanges sable-bentonite compactés avec et sans saturation

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ABSTRACT: In previous studies, the authors have demonstrated an irreversible change in void ratio with suction change of sand-bentonite mixtures after saturation, while that prior to saturation is reversible. However, it has not been clarified how the compression characteristics differ between sand-bentonite mixtures with and without pre-saturation. Therefore, in this study, one-dimensional compression tests were conducted to investigate this. As a result of the compression tests, both types of materials had nonlinear curvature of the compression line, revealing that the compression index of pre-saturated specimens increase. Furthermore, in this study a reproduction analysis of the test results using the SYS Cam - clay model which can consider the effect of soil skeleton structure was performed and good reproducibility could be obtained.

RÉSUMÉ: Dans des études antérieures, les auteurs ont démontré que le changement de l'indice de vide avec le changement de succion des mélanges sable-bentonite lorsque saturation est irréversible, tandis que celui sans saturation est réversible. Cependant, il n'a pas été clarifié en quoi les caractéristiques de compression diffèrent entre les mélanges sable-bentonite avec et sans pré-saturation. Par conséquent, dans cette étude, des tests de compression unidimensionnels ont été réalisés pour le clarifier. À la suite des tests de compression, les deux types de matériaux présentaient une courbure non linéaire de la ligne de compression, révélant que l'indice de compression de l'éprouvette pré-saturée devenait plus grand. En outre, dans cette étude, une analyse de reproduction des résultats des tests à l'aide du modèle SYS Cam-Clay qui peut prendre en compte l'effet de la structure du squelette du sol a été réalisée et il a été constaté qu'une bonne reproductibilité pouvait être obtenue.

Keywords: Sand-bentonite mixtures; suction; compression characteristic; unsaturated soil; elastoplastic.

1 INTRODUCTION

The compaction curve obtained from consolidate on tests for saturated bentonite shows nonlinear curvature and previous studies have discussed this factor. It is shown that for sand-bentonite mixtures there are two zones with different compression lines, with bentonite characteristics at low pressures and sand characteristics at high pressures (Mollins et al., 1996). Regarding the modeling of nonlinear compression lines, there are models that couple an elastoplastic model and water retention (Bosch et al., 2021), but no formulation has been proposed only an elastoplastic constitutive model behaviour. On the other hand, the area above the normal consolidation line is assumed to have be a high structure region and there are elastoplastic models that are expressed in terms of the super loading surface (Asaoka et al., 2002). This model is called SYS Cam - clay model. It is considered that the super loading surface can be used to describe the nonlinear curvature of the compression line. In this study, consolidation tests were performed using saturated and unsaturated sand-bentonite samples to determine the compaction properties. Furthermore, we reproduced the consolidation test using the SYS Cam-clay model, examined the applicability of the model, and examined its applicability to the behavior of compressed bentonite.

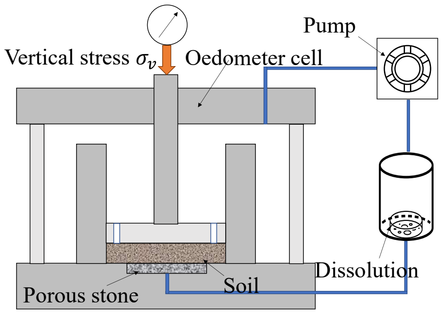

Figure 1. Schematic of the suction-controlled oedometer device using osmotic solution.

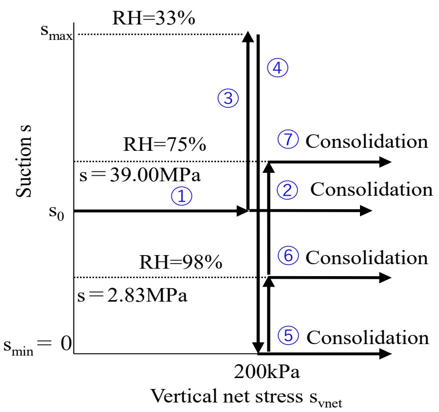

Figure 2. Test procedure.

2 MATERIAL AND EXPERIMENTAL PROCEDURES

The material used in this study is a mixture of sodium bentonite (Kunigel V1, initial water content $w_0 = 8.77\ \%$) and silica sand, with a dry mass ratio of bentonite/silica sand of 7:3. The silica sand is a mixture of No. 5 and No. 7 sand in a weight ratio of 1:1. After adjusting the water content of the mixed specimens to 17 %, they were statically compacted using a high pressure hydraulic press (5 MPa) to produce specimens with a dry density of 1.600 Mg/m^3, a diameter of 60 mm and a height of 10 mm. The test apparatus is a swelling measurement device incorporating a rigid mould inside a pressure-resistant acrylic cylinder, which can also measure swelling forces and deformation by suction change under constant vertical stress loading. The test apparatus is shown in Figure 1. A porous stone is attached to the bottom plate supporting the rigid mould of the test apparatus, and the air flow in the porous stone is connected to the humidity control system through tubes connected to the bottom plate. In addition, a porous stone is attached to the pressure plate having tubular openings in contact with the upper surface of the specimen and is connected to the humidity control system through the perforations. Suction is controlled by the vapour pressure method and humidity is controlled by saturated saline solution.

Two types of specimens (with or without saturation history) were used in this study. The test procedure for this test is shown in Figure 2. First, the specimens were set in a rigid mould and subjected to a vertical stress of 200 kPa to ensure that the compressive deformation reached equilibrium. For unsaturated specimens without saturation history, the consolidation tests are carried out by increasing the vertical stress after the compression deformation has reached equilibrium. For specimens with saturation history, after the compression deformation has reached equilibrium, humidity controlled (RH 33 %) air is circulated through the porous stone at the base and the amount of shrinkage deformation resulting from increased suction is measured. After equilibrium is confirmed, the specimen is saturated by distilled water soaking through the porous stone below, while maintaining the vertical stress loading. For the specimens under saturated conditions, consolidation tests are carried out. In case of unsaturated specimens with two imposed saturation history and a specific suction that the above-mentioned compression tests were performed.

3 EXPERIMENTAL RESULTS

The compression test results for the unsaturated specimen without saturation history compared with consolidation test result for the saturated specimen are shown in Figure 3, and the consolidation test results for the saturated specimen compared with unsaturated specimen with saturation history are shown in Figure 4. For the unsaturated specimen without saturation history, the compression curve becomes straight above 2000 kPa, and for the specimen with saturation, including the saturated specimens, the compression curve becomes a straight line above 800 kPa. Therefore, the dashed line shown in Firure 3 is assumed to be the normal consolidation line in the region above this value. Comparing the unsaturated specimen without saturation history, the unsaturated specimen showed less compressibility and the saturated specimens showed greater compressibility. The slope of the NCL also increases with saturation. Therefore, the structures develop according to suction decreases. The elasto-plastic model presented by Alonso et al. (1990) also considers a model in which the compressive index decreases with decreasing suction, which is consistent with the results of this study.

For the specimens with saturation history, the compression lines tended to converge to the same

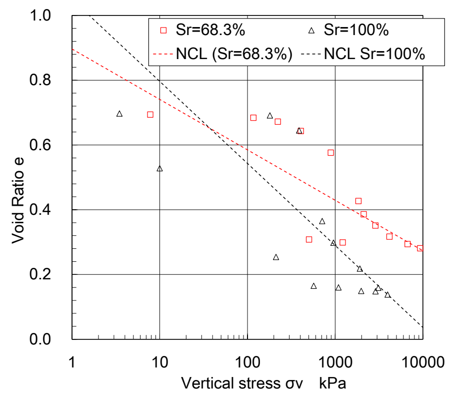

Figure 3. Compression test results of unsaturated specimen without saturation history compared with saturated specimen.

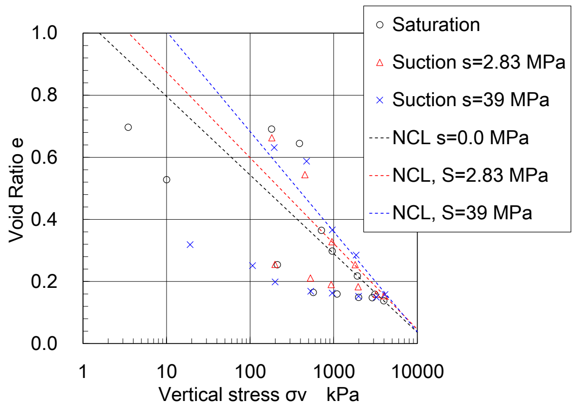

Figure 4. Consolidation results of unsaturated specimens with saturation history compared with saturated specimen.

slope regardless of suction. In terms of the structure, it tended to decrease with decreasing suction. The difference between the samples with or without saturation history is due to the evolutionary differences in the structure and the slope of the compression line under high pressure converge to same line.

4 OVERVIEW OF SYS CAM-CLAY MODEL

With regard to the behaviour of unsaturated or saturated sand-bentonite, the SYS Cam-clay model (Asaoka et al., 2002) was applied. This model was developed based on the Cam-clay model by adding the concept of "structure", "overconsolidation" and "anisotropy" as a soil skeleton structure of soils, and the changes of soil skeleton structure with ongoing plastic deformation was modeled as evolutionary rules. This model can describe the typical mechanical behavior of sand and clay using same theoretical framework, depending on the different speed of the evolutionary rules. In this study, further attempts are applied to this model to sand-bentonite mixture and confirm the effects of saturated/unsaturated condition and the saturation history on the soil skeleton structure, especially focusing on the degree of structure $1/R^*$. Here, structure refers to the bulkiness of soil (a state which can possess a larger void ratio under the same effective stress), and soil with a highly developed structure can take a stress state above the normal consolidation line. Furthermore, since structural deterioration acts as plastic compression, large volumetric compression occurs during structural deterioration. See Asaoka et al, (2002) for the detail.

5 MODELLING RESULTS

In this study, Abaqus was used as the solver and the SYS Cam-clay model was applied for analysis. The analysis method used unit elements and covered the stages from loading to the end of unloading, ignoring pore water. The parameters of the SYS Cam-clay, the initial void ratio e_0, compression index λ and swelling index κ are values obtained from experimental results. The Poisson's ratio is fixed at ν = 0.10 in all cases. As a result of this study, the analysis results for the unsaturated specimen without saturation history

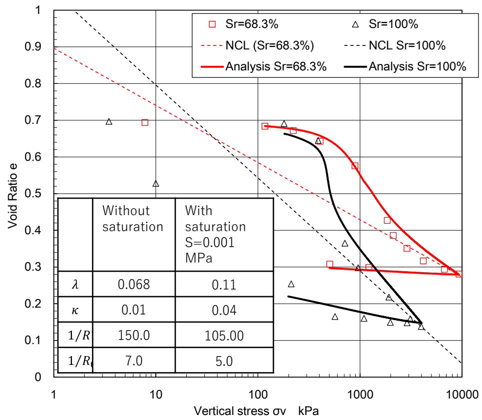

Figure 5. Comparison between consolidation test results and reproducible analysis (specimen without saturation history).

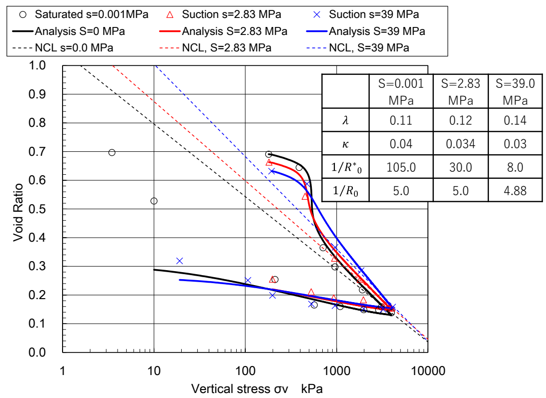

Figure 6. Comparison between consolidation test results and reproducible analysis (specimen with saturation history).

compared with saturated specimen is obtained as shown in Figure 5, while the analysis results for the specimens with saturation history are compared with saturated specimen in Figure 6. The analysis results show a good agreement for the compression lines. Comparing the unsaturated and saturated specimens by Figure 5, the compressive index λ is larger for the saturated specimen, meaning that the compressive index λ increases as suction decreases. Focusing on the degree of structure $1/R^*$, it can be seen that the structure is more highly developed in unsaturated specimens than in saturated specimens. In addition to a larger compression index λ, unsaturated specimens have the characteristic of producing large volumetric compression by the collapse of the structure with ongoing increase of vertical stress. Under large vertical stress condition, the structure becomes degraded, regardless of whether it is saturated or unsaturated, and possesses a stress state on the normal consolidation line. On the other hand, the compression index λ of the specimens with saturation history was almost equal. Focusing on the degree of structure $1/R^*$, it can be seen that the lower the suction, the more significantly the structure is developed. This trend is opposite to that in Figure 5, which has no prior saturation history. From a comparison between Figure 5 and Figure 6, it was found that the presence or absence of a pre-saturation history has a great influence on the subsequent compression properties, especially on the structural development associated with the suction action. The analysis results indicate that the SYS Cam-clay model can be adapted to describe the non-linear compressive behaviour of saturated and unsaturated sand-bentonite specimens with or without saturation history.

6 CONCLUSION

The compressive behaviour of saturated and unsaturated sand-bentonite mixture was obtained by using a suction-controllable consolidation test apparatus with the vapour pressure method. As a result of the study, compression behaviour with non-linearity was obtained for both saturated and unsaturated specimens, and the compression behaviour differed depending on whether the specimens are with or without saturation history. Comparing the compression behaviour of the unsaturated and saturated specimens, the compressibility tended to be small and increased with approaching a saturation. The slope of the NCL also increases due to saturation. For the specimens with saturation history, the compression lines tended to converge to the same slope regardless of suction. In terms of the structure, it decreases with decreasing suction. Furthermore, the SYS Cam-clay model was used to perform the analysis, which showed that the compression behaviour could be reproduced by using the upper load surface. The SYS Cam-cay model can be used to describe the non-linear compression behaviour of saturated and unsaturated sand-bentonite, however a state-specific evolution law is required for the parameters such as the degree of skeletal structure for the specimen with or without saturation history.

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