Strength of Dynamically Compacted Soils

Résistance des Sols Dynamiquement Compactés

H.OHTA and
S.HATA Department of Civil Engineering, Kyoto University, Japan

SYNOPSIS The consolidation and shear strength characteristics of partly saturated soil compacted by the application of static pressure are investigated. The constant volume shear strengths of soil compacted with any kind of dynamic compaction method are shown to be predicted from the informations obtained from the static consolidation and shear tests with the assumption that the mechanical behaviour of dynamically compacted soil is roughly coincident with that of equivalent statically consolidated one regardless of possible difference in micro-structures of dynamically and statically compacted soils. Experimental investigations supporting the proposed strength prediction technique are also presented.

INTRODUCTION

Compacted soil is one of the oldest and plentiest engineering materials we use in the construction of embankments, fills and roads. Proctor test has long given the primary informations about the compacted soils to the engineers designing and constructing these earth structures. However Proctor test is not directly connected with the fundamental engineering characteristics such as shear strength, permeability and deformability of compacted soils. It is still difficult to estimate these fundamental characteristics of compacted soils prior to the performance of trial field compaction with the equipments to be used in the forthcoming real construction works. In this paper presented is a trial to predict the shear strength of dynamically compacted soil from the informations obtained from static consolidation and shear tests.

STATICALLY COMPACTED SOIL

A series of static consolidation and shear tests are performed in a shear box (6cm diameter). The soil used here is a sandy silt (d_{max}=2.0mm, d_{50}=0.58mm, Gs=2.68).

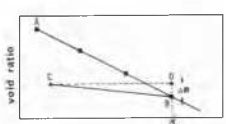

Fig.1
Pressure-void ratio relationship

A key sketch of obtained pressure-void ratio relation is given in Fig.1. Lines AB and BC in Fig.1 are normal consolidation and swelling line respectively. As far as this sandy silt concerns the amount of swell i.e. Δe in Fig.1 is small. So when we plot void ratio e against pre-consolidation pressure σ_c, all the e-log σ_c plots both of normally and overconsolidated specimens are in close proximity to line AB. In this paper we discuss the strength of compacted soil with negligibly small swell. The following discussions can be expanded with some complexity to the soil with considerably large amount of swell.

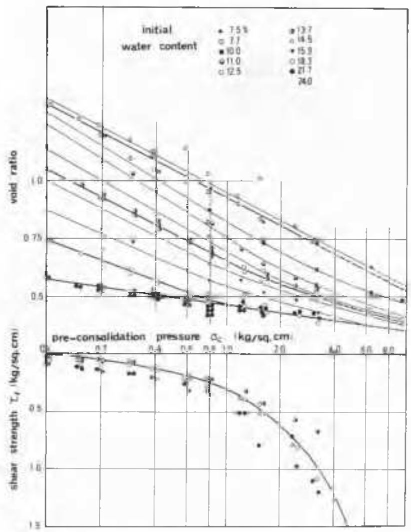

Fig.2 Summary of consolidation and shear tests

The results of consolidation tests are summarized in the upper part of Fig.2 where plotted are the data not only of normally consolidated specimens but also of overconsolidated ones within the range of overconsolidation ratio from 1.5 to 4.0. It is shown that the consolidation curves are roughly parallel lying from the top to the bottom in order of the initial water content. The lowest curve on which black circles are plotted corresponds to high initial water contents (w=21.7 and 24.0%). This curve is the consolidation curve of specimens almost fully saturated.

The specimens thus consolidated in a shear box are then sheared under conditions of constant volume during shear. Volume changes during shear are prevented by controlling the normal stress being applied to the specimen in the shear box. The strengths τ_f obtained from the constant volume shear tests are plotted against logarithm of pre-consolidation pressure σ_c in the lower part of Fig.2. All the plots are roughly on a single curve which is represented by $\tau_f=0.3\sigma_c$. This means the shear strength of statically compacted soil under constant volume shear depends only on pre-consolidation pressure but neither on the void ratio nor on the initial water content. Furthermore it does not depend on the overconsolidation ratio in the case of this particular sandy silt.

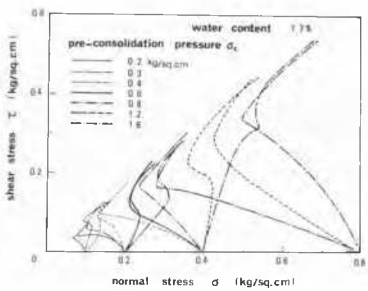

Fig.3 Stress paths during the constant volume shear tests (initial water content 7.7%)

Fig.3 shows the stress paths during the constant volume shear tests on the specimens with initial water content of 7.7%. It is clear that the shear strength depends only on the pre-consolidation pressure but not on the overconsolidation ratio. This must be in consequence of small Δe in Fig.1. In the case of large Δe, things must be more complicated. The authors expect that most of the soils commonly used as the materials of compacted earth structures are sandy silts with relatively small swelling indices compared with compression indices. So following discussions would be applicable to most of the materials of compacted earth structures without having any more complexity.

DYNAMICALLY COMPACTED SOIL

The micro-structures of statically and dynamically compacted soils must be considerably different from each other. This difference in the micro-structure will affect on the mechanical behaviour of these two types of compacted soils. However the authors hope that this effect could be less significant compared with the effects of void ratio, water content, consolidation pressure or dynamic compacting efforts at least for some classes of silty soils, and try to discuss the strengths of dynamically compacted soils by comparing with those of statically consolidated soils. In other words, the authors try to predict the shear strengths of soils compacted by any kind of dynamic method interpreting the informations obtained from static consolidation and constant volume shear tests. So the aim of this study is to get the rough predictions of shear strengths of compacted soils.

In the left hand side of Fig.4 given is the reverse of Fig.2 showing the results of static consolidation and shear tests. Suppose a soil specimen compacted by any particular kind of dynamic method, e.g. by giving a small number of blow of a tamper falling through a certain distance. The void ratio and water content of this compacted specimen are known and can be plotted in the upper right part of Fig.4 as shown by a circle.

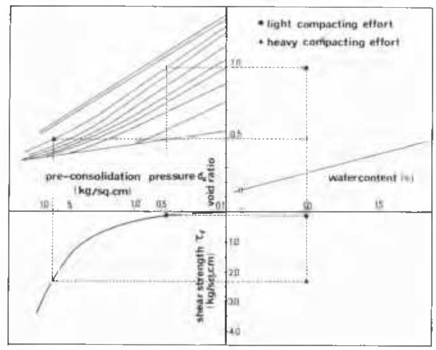

Fig.4 Prediction of strength of compacted soil

If the micro-structure of the soil does not significantly affect the mechanical behaviour of the soil, the shear strength of this dynamically compacted specimen should be close to that of a statically consolidated specimen with void ratio and water content coincident with those of dynamically compacted one. This equivalent statically consolidated state can be plotted in the upper left part of Fig.4 as shown by a circle because we have already got the relations between void ratio and pre-consolidation pressure of statically consolidated specimens with water content as a parameter. Thus an equivalent pre-consolidation pressure of dynamically compacted specimen can be known by the use of the results of static tests. The equivalent pre-consolidation pressure is the pre-consolidation pressure necessary to be applied in obtaining a statically consolidated specimen the void ratio and the water content of which are equal to those of dynamically compacted one. Knowing equivalent pre-consolidation pressure we estimate the shear strength of equivalent statically consolidated specimen as shown by a circle in the lower left part of Fig.4. Thus predicted shear strength of dynamically compacted specimen is plotted in the lower right part of Fig.4 by a circle.

When we compact the soil with the water content equal to that of above mentioned dynamically compacted specimen by dropping the tamper much more times than the previous case, the soil will be more densely compacted as shown by a triangle in the upper right part of Fig.4. By using the same technique applied to the specimen compacted with light compacting effort (circle in Fig.4), we can predict the shear strength of the dense specimen as shown by a triangle in the lower right part of Fig.4. These examples suggest that the equivalent pre-consolidation pressure is not necessarily equal to the maximum pressure which a dynamically compacted soil has ever experienced, because the difference between the specimens compacted with light and heavy compacting efforts are only the number of blow in this case.

In order to examine whether the prediction technique mentioned above works well, comparisons between predicted and measured shear strengths obtained from the shear tests under conditions of constant volume are made for the specimens compacted in a shear box with dynamic, vibratory and impact compaction methods.

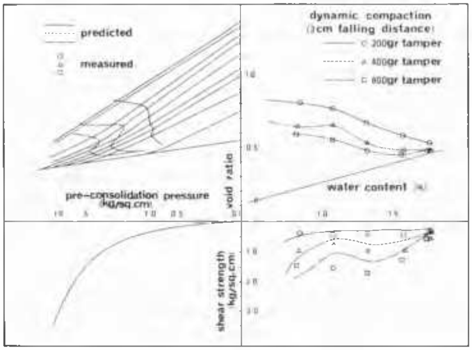

Fig.5 Predicted and measured strengths of soil dynamically compacted with 3cm falling distance of tamper

Fig.5 shows the results of shear tests on the specimens dynamically compacted in a shear box (6cm dia.) with a tamper falling 40 times in a guiding cylinder through a distance of 3cm. The compacting efforts are varied by using three types of tamper; 200gr., 400gr. and 800gr. weight. The diameters of these tampers are within the range from 3.20cm to 3.26cm. The thickness of specimens after compaction is about 1.5cm. The compaction curve given by 800gr. tamper is roughly corresponding to that obtained from Proctor test (ASTM D698, AASHO T99, JIS A1210). The normal stresses prior to the constant volume shear tests are less than equivalent pre-consolidation pressures. It may be worthy to repeat that the constant volume shear strength of statically consolidated soil is not significantly influenced by the overconsolidation ratio, i.e. the current normal stress prior to shearing does not matter as far as the pre-consolidation pressure is fixed.

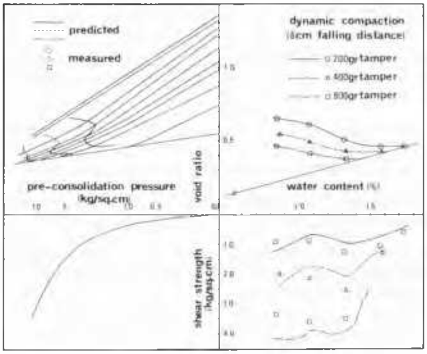

Fig.6 Predicted and measured strengths of soil dynamically compacted with 8cm falling distance of tamper

Fig.6 shows the comparison of predicted and measured shear strengths of specimens dynamically compacted in a same way mentioned above but with the falling distance of 8cm rather than 3cm.

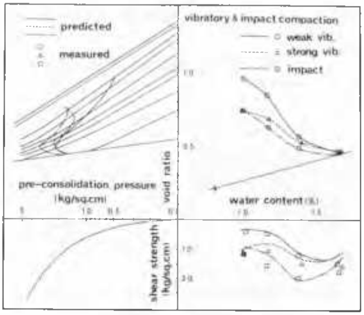

Fig.7 Predicted and measured strengths of soil undergone vibratory and impact compaction

The predicted and measured strengths of the specimens undergone vibratory or impact compaction are given in Fig.7. Vibratory compaction is performed by giving one minute shaking through a vibrator the diameter of which is a little smaller than that of shear box. Impact is given by a tamper falling in a guiding cylinder through a distance of 2cm. The diameter and the weight of the tamper are 5.96cm (nearly equal to the diameter of shear box) and 1140gr. respectively. The number of blow is 40. The thickness of specimens after compaction is about 1.5cm in these vibratory and impact compaction procedures. Figs.5,6 and 7 suggest that the prediction technique proposed here gives rough estimation of constant volume shear strength of dynamically compacted soil regardless of compaction method.

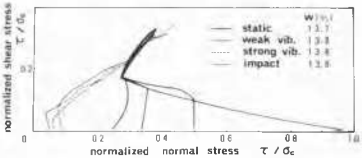

Fig.8 Stress paths of statically and dynamically compacted soil

Stress paths during the constant volume shear on the specimens undergone the vibratory and impact compaction are shown in Fig.8 where the normalized stress paths of statically consolidated specimens are also shown. The overconsolidation ratio of dynamically compacted specimens are determined from the equivalent pre-consolidation pressures devided by the normal stresses applied to the specimens prior to shearing. Unfortunately we do not know the stress paths of statically consolidated specimens which have high over consolidation ratio, so it is difficult to show the stress paths of dynamically compacted specimens exactly coincident with those of statically consolidated specimens with corresponding overconsolidation ratio. But the stress paths of dynamically compacted specimens shown in Fig.8 are compatible to those of statically consolidated specimens. This suggests that the mechanical behaviour of dynamically compacted soil is roughly same with that of equivalent statically consolidated soil. In the authors' opinion Figs.5,6,7 and 8 are considered to be supporting the appropriateness of proposed strength prediction technique at least for the use of rough prediction of constant volume shear strength of soil undergone any particular kind of dynamic compaction.

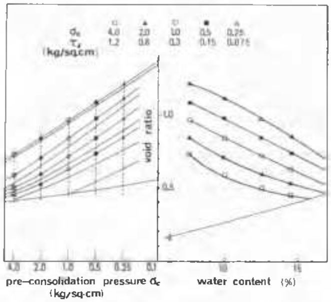

Fig.9 Possible equi-strength contours of dynamically compacted soil

Fig.9 shows the possible equi-strength contours back calculated from the results of the static consolidation and shear tests. These contours given in the right hand side of Fig.9 are similar in their shapes to those experimentally presented by G.Kuno (1963) and O.G.Ingles (1974).

APPLICATION TO PRACTICAL PROBLEMS

Prior to the design and construction of an earth structure made of compacted soil, it is possible to carry a series of static consolidation and constant volume shear tests. By using the results of these static tests, we get a diagram similar to Fig.9 where the contours of equi-constant volume shear strength are drawn. If we consider the constant volume shear strength to be used in the design works, it is easy to designate the relation between water content and void ratio (or dry density) of the compacted soil. As far as the compaction control is carried following this designated w-e relation, the soil compacted in the field with any kind of set of compaction equipment and procedure should have intended constant volume shear strength unless the fill is so high that the own weight of compacted soil exceeds the equivalent pre-consolidation pressure applied by the compaction equipments.

In the case that we have to use more sophisticated concept of shear strength rather than the constant volume shear strength, things are more complicated. We know the equivalent pre-consolidation pressure of soil dynamically compacted in the field and we also calculate the current normal stress on an element located at the possible slip line. Then the equivalent overconsolidation ratio is calculated. We also know the stress paths during the constant volume shear tests on statically consolidated soil the overconsolidation ratio of which is equal to thus calculated in-situ equivalent overconsolidation ratio of the soil element. Applying the concept of effective stress principle, we get the supposed shear strength of compacted soil with constant normal stress for instance. The concept of effective stress should be very carefully applied to the problem because applicability of effective stress principle is still open to question in spite of great deal of existing investigations, e.g. A.W.Bishop (1960), J.E.B.Jennings and J.B.Burland (1962), R.E.Olson (1963). Unpublished work by the authors on model slopes made of compacted soil suggests that the constant volume shear strength would be of practical use in the design of fills.

Most of the embankments, fills and roads are supposed to be submerged at least in a short period. In this case the strength prediction technique proposed here should not be applied. The strength reduction due to soaking can sometimes be considerable depending on the current normal stress and on the drainage condition during shear. It is worthy to note that the constant volume shear strength of compacted soil after soaking depends only on the current normal stress but neither on the initial water content, void ratio nor equivalent pre-consolidation pressure. The effect of submergence on the shear strength of compacted soil will be published in the near future.

CONCLUSIONS

Investigated are the consolidation and shear characteristics of partly saturated sandy silt consolidated with static pressure. It is concluded that the relation between pre-consolidation pressure σ_c and void ratio e is represented by a set of curves in e-log σ_c diagram with the initial water content as a parameter. The shear strength of statically consolidated soil under constant volume shear is a unique function of pre-consolidation pressure regardless of overconsolidation ratio, void ratio and of initial water content. The constant volume shear strengths of soil compacted with any kind of dynamic compaction method are roughly predicted from the results of static consolidation and shear tests assuming the mechanical behaviour of dynamically compacted soil is coincident with that of equivalent statically consolidated soil. Some of the experimental investigations supporting the appropriateness of the proposed prediction technique are presented. Although the assumption used in the proposed technique is proved not to be far from the reality, much more detailed and large scaled investigations should be done on this topic before the prediction technique is used in the practical engineering problems.

REFERENCES

Bishop,A.W. (1960),"The Principle of Effective Stress", Norwegian Geotechnical Institute Publication, No.32, p.1-5.

Ingles,O.G. (1974),"Compaction," Soil Mechanics-New Horizons, Chap.1, Edited by I.K.Lee, Newnes-Butterworths, London, p.1-24.

Jennings,J.E.B. and J.B.Burland, (1962),"Limitations to the Use of Effective Stresses in Partly Saturated Soils," Géotechnique, Vol.12, pp.125-144.

Kuno,G. (1963),"Compaction of Soils," Gihodo, Tokyo (in Japanese).

Olson,R.E. (1963),"Effective Stress Theory of Soil Compaction," Jour. Soil Mech. Found. Div., Proc.ASCE, SM 2, pp.27-45.