Microscopic Study on Deformation and Strength of Clays

L'Etude Microscopique sur la Déformation et la Résistance des Argiles

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SYNOPSIS The study of soil microstructure is a subject which has evoked interest in the basic concepts of stress-strain behaviour of soils. And the quantitative way of expression of the microstructure has been explored and it has been attempted to extend this to the analysis of the engineering properties. In this paper a scanning electron microscope study is dealt with for the changes in soil structure induced during consolidation and shearing deformation. The existence of the particle aggregations in natural clay soils in range of "mesoped", proposed by the authors, is presented. And from the quantitative analysis of structure it is suggested that the particle rotations have been associated with the continuation of consolidation and shearing deformation.

INTRODUCTION

We have many soil engineering problems because soils are multi-phase complexes. And it will be one of the most important points to reveal the physico-chemical properties of soils and to establish the microscopic stress-strain relations of soils. It is evident that clay soils must be regarded from the microstructural point of view. The study of the various levels of soil structure is accepted as essential to a fundamental understanding of the engineering behaviour of clay soils. Therefore, it is very important that the concepts of soil microstructure are extended to more generalized forms. There is now considerable experimental evidence assigning a role to soil microstructure in the bulk behaviour of clay soils.

This paper is concerned with exploring the basic concepts at the microscopic particulate level, and in the basic mechanism of deformation and shearing phenomena.

CONCEPTS ON BASIC UNITS OF MICROSTRUCTURE

According to the observations of the soil microstructure by using the recent scanning electron microscope, it has been recognized that both artificial and natural clay soils are made up of clay plates aggregated into peds (Barden and Sides,1970; Yong and Sheeran, 1973; Collins and McGown,1974; etc.). And it is supposed that these aggregated clay particles are the minimum units controlling the macroscopic mechanical behaviour of clay soils. Also, recently there are many technical terms with respect to the aggregated paticles, e.g. domain, floc, cluster, block, packet, assemblage, ped, etc., and although there is a different nuance among them they generally are used without distinguishable and strict definition, consequently it seems that there is even a confusion in these terminologies.

Table I Peds and pores defined

macroped	(>50 μm)	by naked eye and spy glass
macropore	(>10 μm)	
mesoped	(2～50 μm)	by optical microscope
mesopore	(1～10 μm)	
microped	(0.1～2 μm)	by scanning electron microscope
micropore	(0.01～1 μm)	
submicroped	(<0.1 μm)	by transmission electron microscope
submicropore	(<100 Å)	

In order to simplify and to unify this complication, the authors have defined the terms of "peds and pores" for the basic units constituting the soil microstructure, as shown in Table I. By this definition it may be considered that the ped is the ultimate unit affected by physico-chemical forces. Also, it would like to be assumed that the ped itself is in stable state initially, and that the deformation of the ped is yielded by the external mechanical forces, and the change in the pore inside the ped depends upon the equilibrium of physico-chemical forces. Thus, it will be concluded that the changes in microstructure consist of the correlations between peds and pores, and as a result clay soils have the overall configurations called random, flocculated or dispersed structure.

a) Sedimentation; Initial water content = 250%
b) Consolidation; $p = 0.5\ kg/cm^2$
c) Consolidation; $p = 4.0\ kg/cm^2$
d) Consolidation; $p = 12.8\ kg/cm^2$

Fig. 1 Scanning electron micrographs of Osaka-Nanko clay; electron magnification ×500: picture width = 200 μm

MICROSCOPIC DEFORMATION OF CLAY SOILS

The samples used for this investigation are the natural marine clay (Osaka-Nanko clay) and the mono-mineral clay (kaolinite; Crown clay). They were arranged in slurry state at high water content and were sedimented and consolidated. For the tests of deformation and strength characteristics we used both oedometer consolidation test and constant-volume simple shear test. Water was removed from samples by the pore water replacing and freeze-drying technique. The viewing surfaces were exposed by fracturing and were coated with a thin film of gold in a vaccum evaporator.

The characteristics of deformation of peds from the sedimentation state to the consolidation process of clay soils are shown in Fig. 1. The observation patterns were set in the section of maximum principal stress direction. The diameter of peds measured from the micrographs was the Green diameter, i.e. the constant-direction diameter, for the vertical direction (V-size) and the horizontal direction (H-size) because of the irregular shape of peds and the difficulty of distinguishing between the longitudinal and latitudinal axes. The diameter range measured was 1 μm minimum to 150 μm maximum. Therefore, we treat the peds aggregated in the correlations of the clay and silt size fractions. It is clear that the increase of ped size in the horizontal direction is observed with the progress of consolidation (Fig. 2). The median diameter, D_{50}, ranges from 10 μm to 19 μm and belongs to the "mesoped" range according to the ped size proposed. Fig. 3 shows the ratio of V-size to H-size and Fig. 4 indicates the change in this ratio due to the consolidation. V/H measured decreases from 1.0 to 0.7 with the increase of consoli-

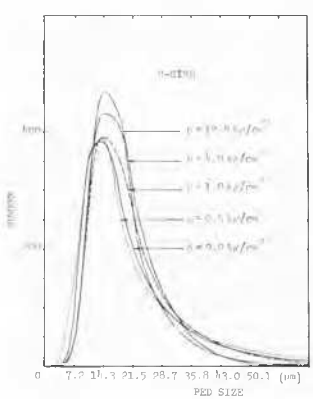

Fig. 2 Histograms of H-size

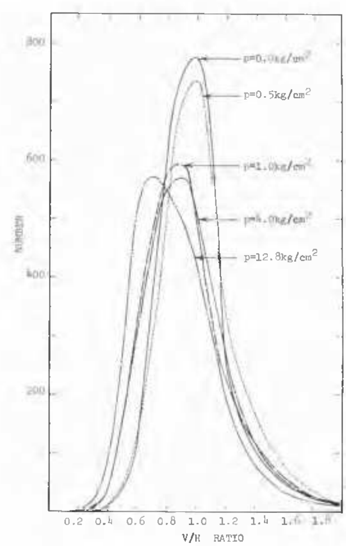

Fig. 3 Histograms of the ratio of the Green diameter

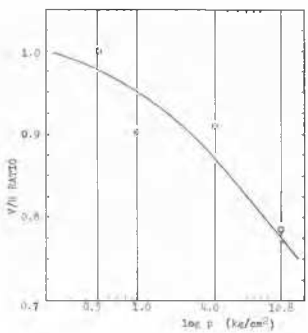

Fig. 4 Change in V/H of D_{50}

dation pressure. This phenomenon shows that the shape of peds were flattened.

The ped size distribution of the perfect dispersed state of sample used is shown in Fig. 5 which was measured by the same technique using the scanning electron microscope. It is clearly seen that the real appearance of clay particles is in the aggregated condition.

QUANTITATIVE EXPRESSION OF THE CHANGE IN MICROSTRUCTURE

Apart from the existence of aggregates like peds, there is a tendency to an overall preferred horizontal orientation of both clay and silt size particles with the degree of orientation being related to the past stress history. As the quantitative expression of this degree of particle orientation, i.e. the factor of soil microstructure, we have adopted the vector magnitude, M-value (Curray,1956; Matsuo and Kamon,1973). Under any stress level, random sampling micrographs have been analyzed.

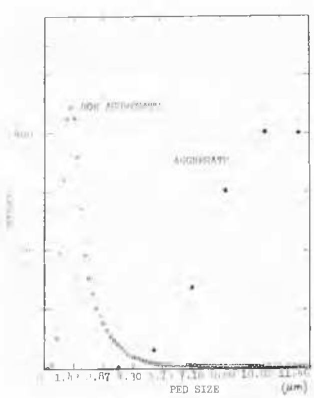

Fig. 5 Ped size distribution of the perfect dispersed state

For the structure study the section of maximum principal stress direction is known to be significant. At first, maximum principal stress direction was considered as the N-S axis and the angles inclining to the longitudinal axes of peds and edges of clay particles forming peds were measured. The examples of frequency histograms measured are shown in Fig. 6. The pattern of remolded samples is shown in Fig. 6 a) and b), and

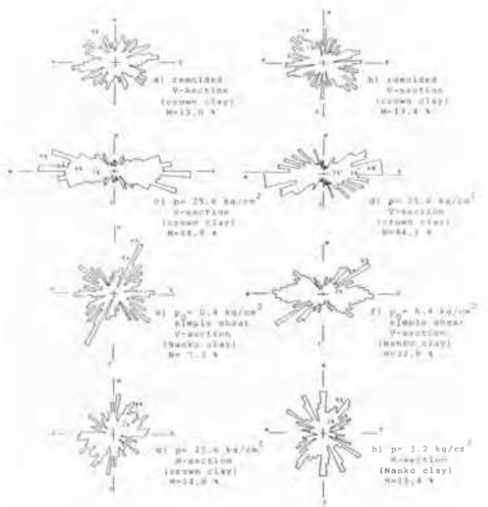

Fig. 6 Frequency histograms of particle inclination

the residuals are in the consolidated state. In the plane of maximum principal stress, the preferred orientation does not take place as shown in Fig. 6 g) and h).

The factor of structure, M-value, is used for the quantitative expression of these differences. M-value was calculated by the following equation.

$$M = \frac{1}{\Sigma n_i} \sqrt{(\Sigma n_i \sin 2\bar{\theta}_i)^2 + (\Sigma n_i \cos 2\bar{\theta}_i)^2}$$

where, $\bar{\theta}_i$; azimuth of group observation,
n_i; number of the observation in each group

The magnitude of one particle is generally

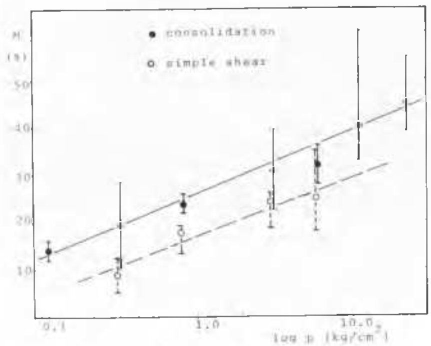

Fig. 7 Change in M-value

considered unity, but it may be other than unity due to weighting by cross bedding dip and by particle size or shape, etc. Fig. 7 indicates the changes in M-value in the consolidation and the shearing performance. The M - log p relation during the consolidation process by the method of least squares is as follow.

$$M = 0.13 \log p + 0.26 \quad (0 \leq M \leq 1)$$

From this result, it may be concluded that the perfect preferred orientation does not take place and the deformation behaviour is pedical at the range of ordinary loading pressure (1 - 5 kg/cm^2, 10 kg/cm^2 at the most). And the observation of microscopic deformation in the secondary compression showed that the rearrangement in peds, especially

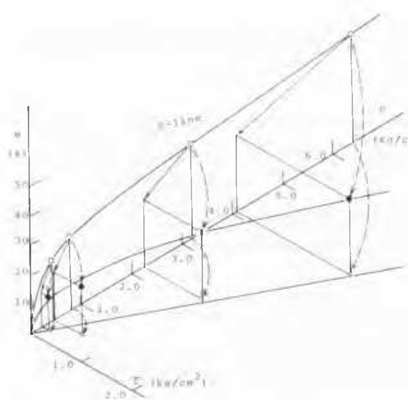

Fig. 8 τ - M - p relations

the decrease of meso- and micropore and the rotation of peds, take place. In Fig. 7 M-values in the simple shear deformation are also plotted against the initial effective stress. It is reported that M-values decrease with the shearing deformation. It is supposed that the clay particles are rotating in peds due to the deformation in the simple shear test. Fig. 8 shows the relations of the shearing stress path to M-value. It is considered that these lines indicate ones of the state surface from the normally consolidated state to failure in any clay soil by means of M-value.

CONCLUSIONS

The following conclusions may be derived from the results of these experimental investigations with respect to the microscopic deformation and shearing behaviour of clay soils.

1) It is found that the natural clay soils comprize peds consisting of clay particles aggregated.

2) It is known that the diameters of peds measured are in the range from 1 µm to 150 µm and the median diameters belong to those of the mesoped.

3) Quantitative expression of the microstructure is successfully given. It might be seen that the factor of structure, M-value, indicated the macroscopic mechanical behaviour of clay soils, especially in the consolidation and simple shear deformation.

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