COMPRESSIBILITY OF A CERTAIN VOLCANIC CLAY

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SYNOPSIS

The settlement of buildings resting on a volcanic clay, known as Kanto loam, shows particular behavior which is quite different from that of sedimentary saturated clay. The authors have been observing for about eight years the actual settlement of buildings built on the Kanto loam. The Kanto loam is a very porous, unsaturated clay. The compression of this clay consists mainly of the initial compression (immediate compression) and the following creep, the consolidation process being practically ignored. This paper deals mainly with an experimental approach to the compressibility of the Kanto loam. Long term compression tests were made and the rate of the creep was observed. It has been observed from these tests that both the volumetric creep and the shearing creep exist and they proceed straightly against the logarithm of the elapsed time. Comparison has been also made between the observed and calculated settlement, and the result shows a fairly satisfactory agreement.

GENERAL DESCRIPTION OF THE KANTO LOAM

The greater part of the upperland of the Kanto district including Tokyo is covered with brown or yellowish brown clays with a thickness of several or more than 10 meters. These brown clays were brought at the diluvial epoch by eruptions of volcanoes located around the Kanto Plain. In Tokyo area the stratum of the Kanto loam is generally less than 10 meters in thickness and often contains a thin layer of fractions of pumice, the lower part being more clayey. Below the Kanto loam follows a dense sandy formation (Fig. 1). Most of the buildings less than five stories high in these areas are safely supported directly on the Kanto loam.

The engineering properties of the Kanto loam are quite different from those of ordinary sedimentary clays. X-ray studies of the clay¹⁾ have shown that it is composed mainly of amorphous allophane and in its lower part existence of hydrated halloysite is evident.

An example of the index properties of this clay is shown in Table 1. The samples were taken at the site of the Building Research Institute, whence samples for main tests described below were also taken. It is noticeable that it is very porous and highly plastic in a remolded state. According to the studies of Misono and others²⁾, the Kanto loam consists of aggregations of 0.02 to 0.06 mm in size which can not be disintegrated into a smaller size by usual mechanical agitations. However, when the clay is dispersed by means of a chemical treatment, the clay content is found more than 50 per cent.

They have been overconsolidated with a preloading stress of 2 to 5 kg/cm² which

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Table 1. Index Properties of the Kanto Loam

Specific Gravity	2.83 g/cm ³
Unit Weight	1.19 g/cm ³
Water Content	120%
Void Ratio	3.92 g/cm ³
Degree of Saturation	85%
Sand Content	12%
Silt Content	30%
Clay Content	58%
Liquid Limit	136.0%
Plastic Limit	81.1%
Plastic Index	54.9
Unconfined Compression Strength (Undisturbed)	2.4 kg/cm ²
Unconfined Compression Strength (Remolding)	0.25 kg/cm ²
Sensitivity	9.6
Preloading Stress	2.2 kg/cm ²
Compression Index	

might have been caused by partial drying or some chemical process. There exist many hair cracks and pin holes, which are predominant in the upper part. In most cases they are unsaturated. Therefore, the consolidation process may be ignored

Fig. 1. Typical Boring Log in the Upper Land of Tokyo

Fig. 2. Comparison between Vertical and Horizontal Strains under the Isotropic Pressure

practically in the compression of the Kanto loam. Since the total pressure is carried by the intergranular stress soon after loading, the progressive settlement following the initial settlement is due to the dislocation of soil grains or the creep; when a load is applied on the Kanto loam, the initial compression (elastic compression) occurs first and the creep follows.

$$\varepsilon(t) = {}_o\varepsilon + {}_c\varepsilon(t)$$

${}_o\varepsilon$: initial strain

${}_c\varepsilon$: strain due to creep

INITIAL SETTLEMENT

In spite of the existence of many cracks and pin holes, the Kanto loam is considered to be macroscopically homogenous soil from its aeolian origin. Figure 2 shows the comparison of vertical and horizontal strains caused by isotropic pressures. The specimens were 14 cm in height and 7 cm in diameter, and all-round pressure was applied. The lateral deformation was measured directly with an accuracy of 0.001 mm by means of a specially devised instrument³⁾. The result shows that the soil is quite homogeneous in this sense.

The results of many compression tests show that compressive strains of the clay are approximately proportional to the stresses lower than the half of the ultimate strength.

Based on the results mentioned above, the initial settlement of a footing resting on the Kanto loam may be estimated by using the theory of elasticity, if the elastic constants are given.

Fig. 3. Relationship between Young's Modulus and Compressive Stress

Fig. 4. Plate Bearing Test on the Kanto Loam (Load-initial Settlement)

According to many compression tests on the Kanto loam, the Young's modulus is roughly proportional to the compressive strength and is given by

$$E = 145q_c \dots\dots\dots (1)$$

where q_c is the compressive strength ($\sigma_3 = 0.5 \text{ kg/cm}^2$)

Poisson's ratios measured are plotted against compr. stress/compr. strength in Fig. 3. Provided that a lateral deformation is to a certain degree restrained, the Poisson's ratio ranges from 0.1 to 0.2. These values agree well with the results obtained from the wave velocity measurements in the Kanto loam⁴⁾.

Figure 4 shows the results of the plate bearing tests on the Kanto loam with various sizes of the loading plate. Initial settlements were taken from readings at 10 minutes after loading.

CREEP SETTLEMENT

A long term plate bearing test was conducted on the Kanto loam. A cube of practically undisturbed Kanto loam was taken out of a test pit and enclosed in a steel box, the surface of which was sealed with grease and rubber sheets. The gaps between the soil and the wall were filled with gypsum. The test was performed in a humid room at a constant temperature. The diameter of the loading plate was 5 cm and the intensity of the load was 1.5 kg/cm^2 . The settlement of the plate was observed for about 4 months.

The result is shown in Fig. 5. A considerable initial settlement as much as 0.6 mm occurred suddenly after loading. The settlement proceeded so gradually for several days and then followed a straight line but with a steeper slope when plotted against the elapsed time on semi-logarithmic paper. According to observations for about 8 years of actual settlements of buildings founded on the Kanto loam, the slope $\frac{d}{d(\log t)} S$ at the straight portion on the S -log t curve does not change its value for the period. We will call it the rate of logarithmic creep settlement and designate it as $\bar{S}$.

In order to investigate the laws governing the creep settlement of the Kanto loam, we made long term compression test varying the stress condition, in which lateral strain was measured directly as well as the axial strain. All the tests were performed

Fig. 5. Creep Measurement on Plate Bearing Test

at a constant temperature. The specimens were prepared from block samples taken from the same test pit as the soil block used for the plate bearing test. The average index properties of the samples have already shown in Table 1.

Test A: Observation of Creep under Isotropic Stress

When a specimen is subjected to an isotropic pressure, the strain will be caused only by the volumetric compression since there exists no shear stress. In this case

$$\epsilon_1 = \epsilon_3 = \frac{1}{3}\epsilon_v$$

The tests were conducted for about 3 months under a constant isotropic pressure and the axial strain was observed. The lateral strain was also observed on some specimens. The pore pressure was measured on one sample and it was found that it had disappeared within a few minutes after loading. An illustrative example is shown in Fig. 6.

Fig. 6. Creep under the Isotropic Stress

First the initial compressive strain of about 25×10^{-4} occurred, then the strain increased some amount for several days and even after that it proceeded straightly with a very small tangent with respect to the logarithm of the elapsed time.

Test B: Observation of Creep under Deviator Stress

Under an anisotropic pressure the deformation of specimen is due to both the compressive and shear strains, since the shear stress exists as well as the compressive stress. The volumetric strain is expressed as

$$\epsilon_v = \epsilon_1 + 2\epsilon_3 \dots\dots\dots (2)$$

and the distortion due to the shear strain is proportional to

$$\epsilon_t = \epsilon_1 - \epsilon_3 \dots\dots\dots (3)$$

Long term unconfined compression tests were made the specimens sealed with a

rubber membrane, and the axial and lateral strains were observed for about 4 months. ϵ_1 and ϵ_3 are plotted against $\log t$ in Fig. 7 (a), and ϵ_v and ϵ_t in (b).

Fig. 7. Creep under the Deviator Stress

ϵ_1 : After a very gentle increase over a period of several days presented by a slightly upward curvature, it went on straightly with a steeper slope with respect to $\log t$.

ϵ_3 : ϵ_3 was of the nearly same trend as ϵ_1 , the slope of ϵ_3 after several days being slightly less than a half of that of ϵ_1 .

ϵ_v : The volumetric strain increased so slowly even after several days, with the same trend as seen in the previous figure.

ϵ_t : The shear strain proceeded with a steeper slope after several days.

Test C: Observation of Creep under Various Stress Conditions

Creep tests were conducted on the Kanto loam using a specially devised triaxial apparatus, where the stress condition was changed in three steps. Firstly, an isotropic pressure 0.4 kg/cm^2 was applied. At this stage no shear stress exists and only a small amount of volumetric creep was observed. Then, the axial load was applied.

At this stage shear creep corresponding to the shear stress occurred. Finally, keeping the shear stress unchanged, the volumetric stress was doubled. While the shear creep did not change its trend, the rate of the volumetric creep increased according to the increase of the mean principal stress.

Fig. 8. Creep under Various Stresses

The experimental results described above may lead to the following conclusion.

1) The strain of the Kanto loam proceeds through two stages after initial strain. The earlier stage lasts for several days where the volumetric strain is pronounced. Total strain during this stage, $\epsilon(t_1)$ is roughly proportional to the initial strain as shown in Fig. 9. They appear to be a phenomenon somewhat analogous to the elastic after-effect. Since at all events, it occupies only a minor part of the whole strain which is considered to occur for a long time, we will put it out of consideration for the time being. In the following stage the shear strain predominates and the strains proceed straightly for many years on semi-logarithmic paper. We will define, in this paper, the progressive strain in this stage as the creep.

2) Possibly the volumetric creep, as well as the shear creep may exist. The former may be caused by the flow of soil particles into voids.

From measurements of the creep rates under various stresses, it is seen that the yield stress necessary to cause creep is very low in this clay, and the rates of the loga-

Fig. 9. Relation between Progressive Strain in Earlier Stage (Elastic After-Effect) and Initial Strain

Fig. 10. Relation between the Logarithmic Creep Rate and Stresses

rithmic volumetric creep and shears creep are nearly proportional to the mean principal stress and the deviator stress, respectively, as shown in Fig. 10. Therefore, the rate

of strain after several days will be given by

$$\bar{\epsilon}_v = \frac{d}{d(\log t)} \epsilon_v = \epsilon \beta_1 \sigma_m \dots\dots\dots (4)$$

$$\bar{\epsilon}_t = \frac{d}{d(\log t)} \epsilon_t = 6\beta_2 \tau_m \dots\dots\dots (5)$$

where

$$\sigma_m = \frac{1}{3}(\sigma_1 + 2\sigma_3), \quad \tau_m = \frac{1}{2}(\sigma_1 - \sigma_3) \dots\dots\dots (6)$$

From the above, using Eq. (2), (3) and (6) the rates of the logarithmic axial creep and radial creep will be given by

$$\bar{\epsilon}_1 = \frac{d}{d(\log t)} \epsilon_1 = \beta_1 \sigma_m + 4\beta_2 \tau_m \dots\dots\dots (7)$$

$$\bar{\epsilon}_3 = \frac{d}{d(\log t)} \epsilon_3 = \beta_1 \sigma_m - 2\beta_2 \tau_m \dots\dots\dots (8)$$

β_1 and β_2 are called the coefficients of logarithmic volumetric creep and shearing creep, respectively. The observed values of β_1 and β_2 range, with a few exceptions, as follows:

$$\beta_1 = 1.5 \text{ to } 4.2 \times 10^{-4} \text{ cm}^2/\text{kg}$$

$$\beta_2 = 3.5 \text{ to } 7.5 \times 10^{-4} \text{ cm}^2/\text{kg}$$

CREEP SETTLEMENT OF A LOADED AREA

For simplicity in the analysis, only points on the axis of symmetry below a foundation will be considered.

If at the points under consideration σ_1 and σ_3 are the vertical and horizontal stresses respectively, then after application of load they are

$$\sigma_1 = \gamma z + \Delta\sigma_1$$

$$\sigma_3 = K\gamma z + \Delta\sigma_3$$

where γ is the unit weight of the soil and K is the earth pressure coefficient at rest.

Using Eq. (6), (7) and (8), the rate of the logarithmic creep settlement of the footing resting on the Kanto loam of thickness H is given by

$$\begin{aligned} S &= \beta_1 \int_0^H \sigma_m dz + 4\beta_2 \int_0^H \tau_m dz \\ &= \frac{\beta_1}{3} \int_0^H \{(1+2K)\gamma z + (\Delta\sigma_1 + 2\Delta\sigma_3)\} dz + 2\beta_2 \int_0^H \{(1-K)\gamma z + (\Delta\sigma_1 + \Delta\sigma_3)\} dz \dots\dots (9) \end{aligned}$$

If the thickness of the clay is moderately large, compared with the footing width, Eq. (9) will be reduced to

$$S = \frac{1}{6} \beta_1 [(1+2K)\gamma H_e^2 + (1+2\lambda)H_e q] + \beta_2 [(1-K)\gamma H_e^2 + (1-\lambda)H_e q] \dots (10)$$

$$H_e = 2 \int_0^H \frac{\sigma_1}{q} dz$$

$$\lambda = \int_0^H \Delta \sigma_3 dz / \int_0^H \Delta \sigma_1 dz$$

The first term of Eq. (10) expresses the effect due to the volumetric creep and the second term due to the shear creep. H_e and λ depend only on the geometrical figure of footing and are calculated by Boussinesq's formula. In the case of a rigid circular footing of diameter B ,

$$H_e = 1.57B \quad \lambda = 0.08 \quad (\text{assuming } \nu = 0.15)$$

The observed rate of logarithmic creep settlement in the plate bearing test shown in Fig. 5 was 0.0058 cm per log cycle of time and the calculated one was 0.0065 cm per log cycle of time, assuming $K = 0.3$. The agreement is fairly satisfactory.

OBSERVED AND CALCULATED SETTLEMENT OF A BUILDING ON THE KANTO LOAM

The authors have made observations for about 8 years of the settlement of several

Fig. 11. Soil Profile and Soil Properties

buildings resting on the Kanto loam.

Here, the observation result of a 4-story apartment house, 56 m long and 5.5 m wide, will be shown.

Fig. 12. Settlement During Construction

Fig. 13. Observed and Calculated Settlements Calculated

The building was constructed in 1954 at Hitotsugi-matchi, Minato-ku, Tokyo. The site is overlaid, below a fill of 1 m thick, by the Kanto loam up to a depth of 7 to 8 m below ground surface. The shear strength of this Kanto loam is lower than that of the usual ones and ranges from 0.3 to 0.5 kg/cm². A dense fine sand formation follows below the Kanto loam (Fig. 11).

The building is supported by individual footings with an average load intensity of 6 t/m² at a depth of 1.2 m below the surface.

Ten reference points were fixed at the footings with nearly equal spacings, and a bench mark reaching to the sand formation was constructed.

Observed settlements during the construction are plotted against the acting foundation pressures in Fig. 12. It is seen that the settlement increases proportionally with an increase of the foundation pressure. The settlement during the construction consists mainly of initial settlement. The straight line in the figure represents the initial settlement calculated using Eq. (1).

The progression of the settlement is shown against the logarithm of the elapsed time in Fig. 13. The mean of the rate of the logarithmic creep settlement is 1.6 cm per log cycle of time. The calculated rate is 1.32 cm per log cycle of time which is seen to be good agreement with the observations.

REFERENCES

- 1) T. SUDO: Clay minerals, 1953, Iwanami, Tokyo.
- 2) S. MISONO and S. SUDO: Studies on the micro-structures of soil, 1958, *Report of Agri. Institute*.
- 3) Y. KOIZUMI and K. ITO: Device for measuring the lateral strain in the compression test of unsaturated clays, 1962, *J. of soil and foundation*, No. 42.
- 4) K. IIDA: Behavior of soil due to a change of water content, 1942, *Research of foundation*, No. 50.