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Long-Term Settlement of Diluvial Clays and Existing Pellets in Seabed

By

Koichi AKAI, Masashi KAMON and Ken-ichi SOGA
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Abstract

The fecal pellets in marine clay layers and their appearance are introduced. They have the role for the cementation of diluvial clay layers in seabed. The void ratio of these layers has been kept too large instead of their high shearing strength. Recently, examples of large settlement of diluvial clay layers due to the reclamation in off-shore projects have been observed. In this paper, it is shown that the large void ratio due to the cementation effect by pellets is one of the main causes for the delayed compression of diluvial clay layers.

Introduction

With the development of marine engineering, construction sites in sea water have been extended from near-shore to off-shore sites. Under such circumstances, information relating to the mechanical properties of seabed strata is necessary from the various fields, especially as regards the consolidation characteristics of deep clay layers, for which we have no economical means for soil improvement.

Under the Quaternary period, several layers of sand-gravel and clay strata have alternately accumulated in the Tokyo Bay and the Osaka Bay areas due to the climatic change and the crustal movement. These areas are the most active industrial and commercial regions in Japan. There are already many construction projects under way, as well as others designed for the future. The Kansai International Airport Project is the biggest one among them. This airport will be constructed on a man-made island (511 ha) under reclamation. The total settlement prediction and measures to mitigate the diferential settlement of clay strata in seabed are the difficult problems of this project.

It has been reported that there are many egg-shaped fecal pellets (about 1.0

Department of Civil Engineering, Kyoto University

-0.6 mm long) in marine clay, and they make up more than 30% of the dried samples (Nakaseko, et al., 1985). These fecal pellets are regarded as having considerable strength, because they can be found in diluvial clay strata. It is considered that the volume of the pellets will be the index of the cementation of clay strata in the seabed.

In this paper, the results of observations made of the settlement of diluvial clay layers due to the reclamation for man-made islands are introduced. Their relation to the existing pellets in the marine clay layers in Osaka Bay is discussed.

Settlement Behavior of Diluvial Clay Strata

Outline of Osaka Bay Reclamation Projects

The coastal reclamation works have contributed greatly towards creating industrial, residential and port areas in Japan, and for attaining the Japanese economic success. Osaka Bay is one of the most progressive areas being reclaimed. Reclaimed areas in and around Osaka Bay, illustrated in Fig. 1, are about 100 km², including projects of the near future.

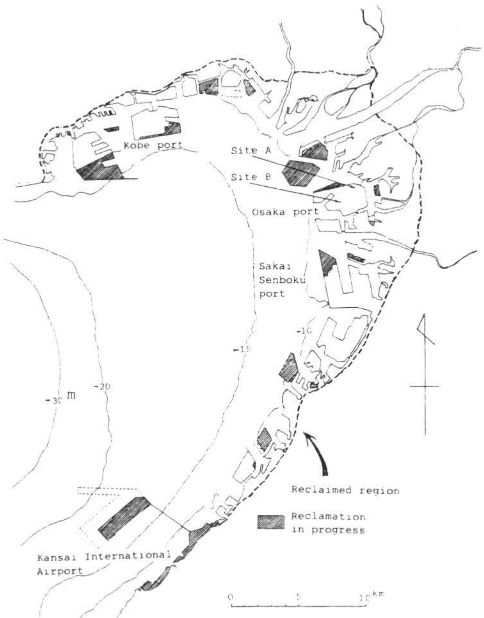

Fig. 1 Reclamation area of Osaka Bay.

Past reclamation works were limited to near-shore sites, and thus, the sea water depth was less than 10 m. According to the increase in demand for man-made islands, the sea water depth subjected for reclamation increased to more than 15 - 20 m. Generally, the seabed soil condition in Osaka Bay consists of alternating strata of clay soils and sand or sand-gravel soils. It has alternating patterns of marine and nonmarine sediments. The surface layer is an alluvial clay and its depth is about 20 m around Osaka Port. Diluvial layers are underlying the alluvial clay, and their profile alternating clay and sand soils continue down to a 500 - 700 m depth. The series of diluvial marine clay layers are numbered as Ma 12, Ma 11, etc. Their ages are estimated as being more than 20000 years.

Following the scale up of the reclamation works, we have to consider the consolidation settlement of these diluvial clay layers (Akai, 1983).

Observed Settlement in Diluvial Clay Strata

An example of the observed settlement of diluvial clay layers is shown in Fig. 2. At the Osaka South Port Project, a long-term settlement measurement has been carried out at the sites A and B in Fig. 1. Site A is close to the quay wall in the man-made island, and site B is the center part of the reclamation. The double tube type settlement gauges were installed at the top of the diluvial soil and at the bottom of the upper diluvial clay layer (Ma 12). At site A, the increasing consolidation pressure due to the reclaimed fill material is about 77% of the pre-compression stress (p_c) of the upper diluvial clay. That is, the overconsolidation ratio (OCR) is 1.3. The settlement of the diluvial soils has been only 13 cm during 11 years. On the other hand, at site B, the increasing pressure corresponds to 90% of p_c(OCR= 1.1). Thus, the total settlement of diluvial soils comes up to 50 cm during 8 years. It is seen that the long-term

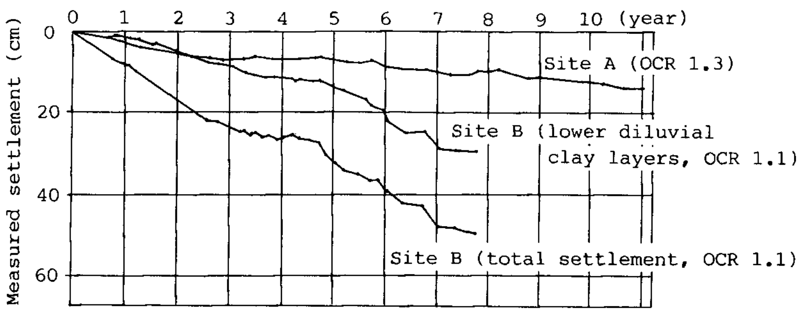

Fig. 2 Settlement of diluvial clay layers in Osaka South Port.

consolidation settlement in the lower diluvial clay layers (from under Ma 11) still continues although the consolidation in the upper diluvial clay has almost finished.

Appearance of Fecal Pellets

Extracting Method of Fecal Pellet

Fecal pellets became observable only when etched by water-jet from an ordinary spray. By this method, clay particles on the cut plan were washed out, and the sedimentary structures and fecal pellets appeared clearly. They are observed gathering together in most cases, but in some cases they were distributed separately in a random manner.

Fig. 3 Pellets in marine clay layer (Ma12).

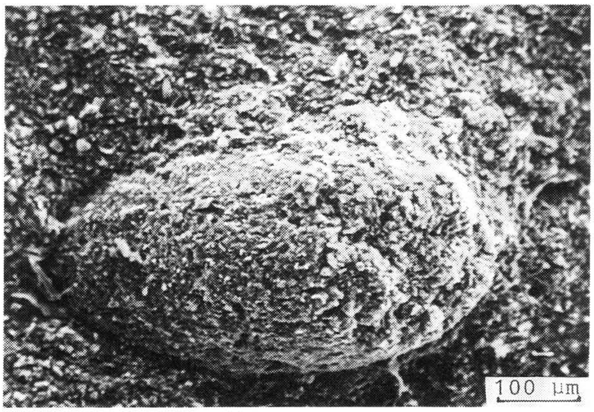

Fig. 4 Pellets in marine clay layer (Ma11).

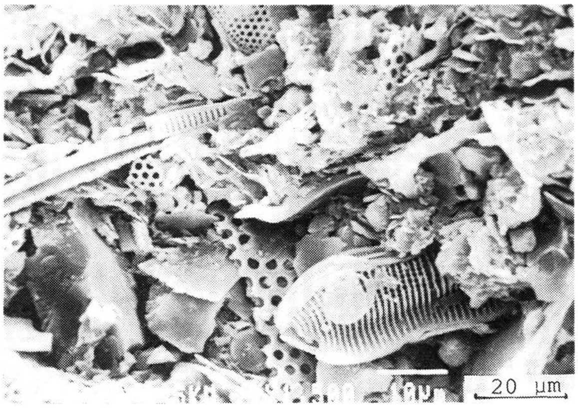

Fig. 5 Inside of pellet.

According to the observation of a scanning electron microscope, most of the fecal pellets have the shape of a cylinder, with both ends tapered hemispherically (Figs. 3 and 4). Their sizes vary from 0.1 − 0.8 mm and the length to thickness is about 2 : 1. There is no conspicuous internal structure within them as shown in Fig. 5. They consisted of skeletal remains of micro-organisms such as diatoms and nannofossils and clay minerals.

The method for extracting these fecal pellets is as follows: After drying the undisturbed clay sample in the air for 18 − 36 hours, the sample is slaked in water. By shifting through a 75 μm sieve, fecal pellets are extracted. The sandsize materials left on the sieve consist of real sand and fecal pellets. After fully dispersing this fraction, the weight percent of the particles which is less than 75 μm corresponds to the pellets contents.

Existing Pellets and Void Ratio of Marine Clay Strata

Fig. 6 demonstrates the ratio of fecal pellets in Osaka Marine Clay. We decided that any weight over 75 μm clay aggregate represents fecal pellets as mentioned above. Fecal pellets in an alluvial clay layer are hardly observed, and are less than 5 %. Even when the fecal pellets in alluvial clay are observed by SEM, the intensity of these pellets is so small that, probably, fecal pellets have been broken by slaking. In Ma 9 -Ma 12, about 15 − 20% of the clay is fecal pellets. Pellets exist even in Ma 9 which is under a large effective overburden pressure. Thus, the intensity of pellets can be expected to be very large. The change of the water content in Fig. 5 corresponds to that of the consistency. It has the shape of a bow reflecting the water level (There is an unconformity plate at the top of Ma 12). Generally, it is thought that the deep marine strata

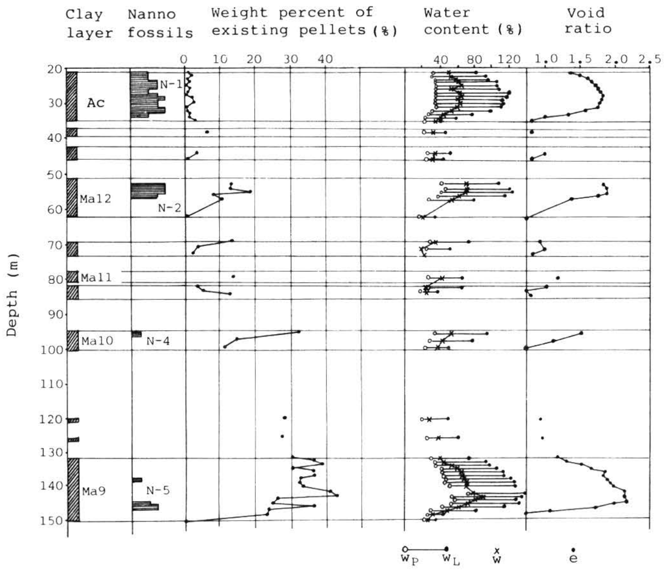

Fig. 6 Existing pellet content and physical properties of core sample in Osaka South Port.

had been consolidated, and the water content decreased by effective overburden pressure. However, this trend can not be seen in Fig. 6. Water contents change from 50% to 80% in each marine stratum, and there is no decrease on the whole. Even the void ratio does not decrease by the consolidation of effective overburden pressure after sedimentation (Kamon, et al., 1987).

Long–Term Consolidation Characteristics

Properties of Secondary Compression

Fig. 7 shows the relation among the void ratio, pre–compression stress and plasticity index in Osaka marine clay strata. The clay samples may be grouped into those having about the same plasticity indices, that is, the same mechanical properties. We used the plasticity index as a parameter of each clay sample in diluvial layers, because these layers are considered to come from the mountainous parent rocks surrounding Osaka Bay.

In spite of an increase in overburden pressure, the decrease in the void ratio by consolidation was found to be very little. If we regard Fig. 7 as representing the e–log p relationship of the consolidation test, the compression index C_c is about 0.1 – 0.3. However, the results of the standard consolidation tests on the same samples showed C_c to be 0.7 – 2.0 as shown in Fig. 8. In the deep part of

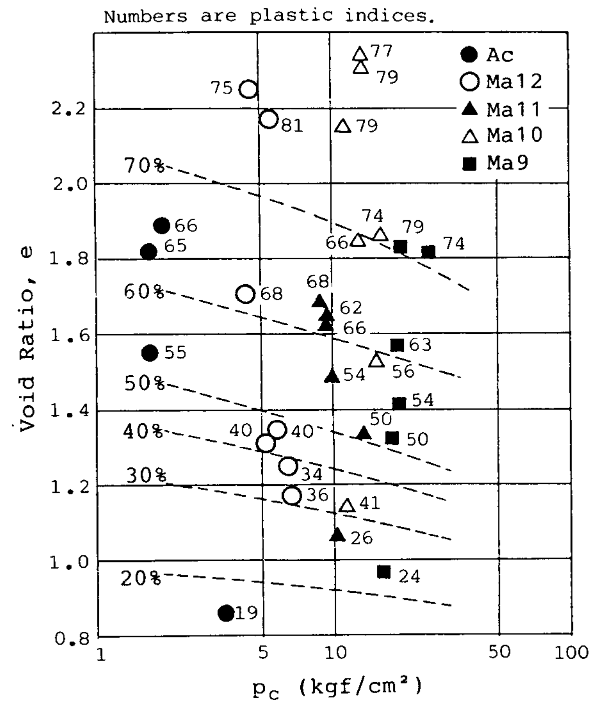

Fig. 7 Difference of void ratio due to cementation and aging.

marine ground, something must have taken place to keep the void similar to the original state when the clay sediments were deposited. One of the causes might be the cementation between clay particles. However, it is hard to imagine that the cementation occurred just after they accumulated. Therefore, it is considered that these fecal pellets which form very large structural units have kept the effective overburden pressure and prevented the decrease in pore space in the clay layers. The high void ratio in the diluvial clay layer is caused by such stress holding effect of the pellets in addition to the cementation taking place during aging.

As long-term consolidation characteristics of diluvial clay layers, the coefficient of the secondary compression, C_α, is obtained under various surcharge pressure. At a surcharge stress less than the pre-compression stress p_c, the settlement due to the secondary compression is very little. However, at the surcharge over p_c, C_α increased with time and also the rate of consolidation settlement increased. So we have to be very careful with the settlement characteristics when the surcharge is over p_c. To know the effect of the pellets

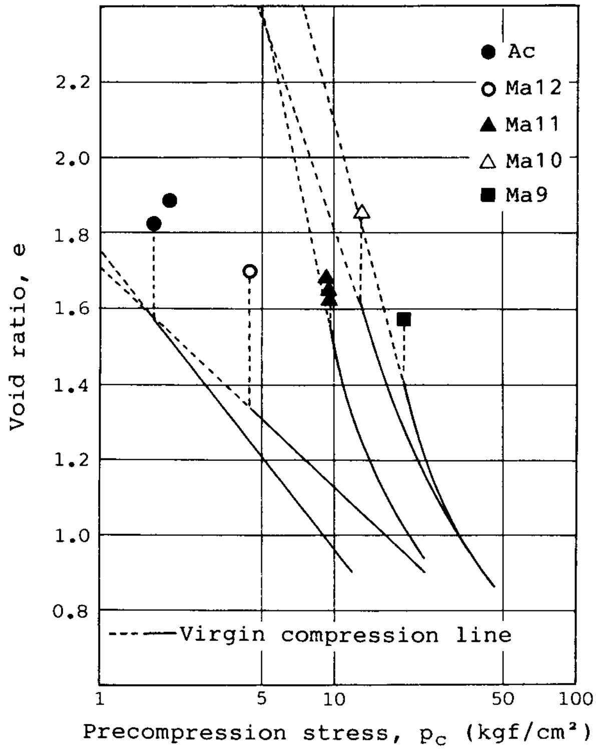

Fig. 8 Pre-compression stress of marine clay and corresponding in-situ void ratio.

on the long-term consolidation characteristics, especially from the view point of the strength of the pellets, we observed the pellets in the samples which have been subjected to the long-term consolidation test. There is no particular decrease in pellet content after being subjected to the surcharge pressure over p_c. So the pellets are considered to be strong enough to stay intact even under such severe conditions as the rapid loading ratio of laboratory tests and the surcharge pressure of over p_c. Fig. 9 shows the C_a-values at each surcharge. The stress, at which C_a shows the peak, is about 2-5 times the pre-compression stress.

Prediction of Sedimentation Process

Under the sedimentation process, the clay deposits themselves have been consolidated by their own overburden pressure. However, the values of the void ratio in diluvial clay layers are not so small as to equal the results obtained from the laboratory consolidation tests. While using the compression index (C_c) and C_a due to the consolidation tests, the calculated void ratio, which is consolidated

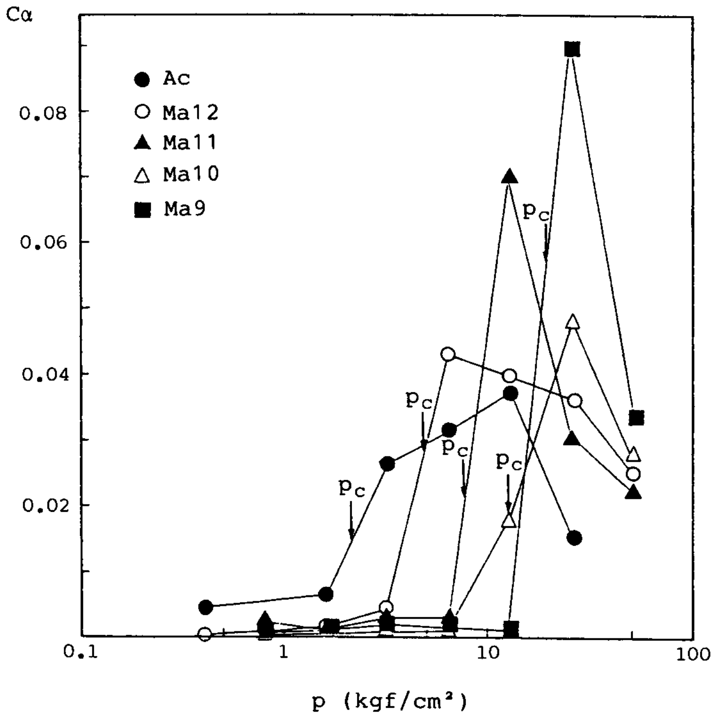

Fig. 9 Representative C_α-values of marine clay strata.

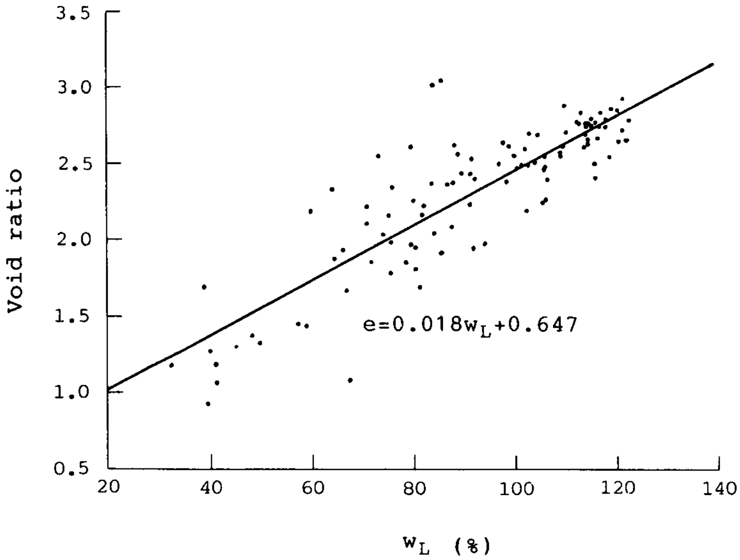

Fig. 10 Void ratio predicted at p=0.3 kgf/cm² by consolidation test results vs. their liquid limits.

by the corresponding overburden pressure and decreased by the secondary compression effect in the laboratory, and the real in situ void ratio are carefully compared. It is very difficult to determine the original state of the void ratio just after the time of sedimentation. We can predict their initial void ratio as follows: The original state of the void ratio should be on its e- log p line of each sample. Because the surface of the seabed is unstable, the state of $p = 0.3\ kgf/cm^2$, which corresponds to the 3-5 m depth, is selected as the initial void ratio. Using the relation between the liquid limit and the compression index which is linear, a different initial void ratio for every different clay sample is calculated as shown in Fig. 10.

The in situ void ratio is compared with the calculated value, which is considered to be the consolidation by the overburden pressure and the secondary compression by the time effect, as shown in Fig. 11. In the alluvial clay (Ac), the calculated void ratios are larger than the in situ values. It is seen that the rapid loading by the reclaimed fill pressure causes a large settlement in the whole layer. On the other hand, in the diluvial clay layers, the calculated values are smaller than the in situ ones, especially in the Ma 9 layer. This means that the consolidation due to the cementation and the time effect is greatly delayed, and the decreasing void ratio by the overburden pressure is greatly restrained. It is concluded that the relatively large settlement of the diluvial clay layers, as mentioned in Fig. 2, is caused by the delayed consolidation of these large voids in clay soils.

Conclusions

Many pellets found in marine clay strata remain intact during a long-term consolidation process such as sedimentation. Especially in diluvial clay strata, they get hardened by cementation and aging. This forms the cause for the large void ratio of the diluvial clay layers in spite of their high overburden pressure.

It is recommended that we must carefully estimate the prediction of settlement when planning off-shore big reclamation projects. Even now, there are many unsolved problems relating to the consolidation characteristics of diluvial clay strata. Information on the behavior of fecal pellets will surely contribute to solve these problems.

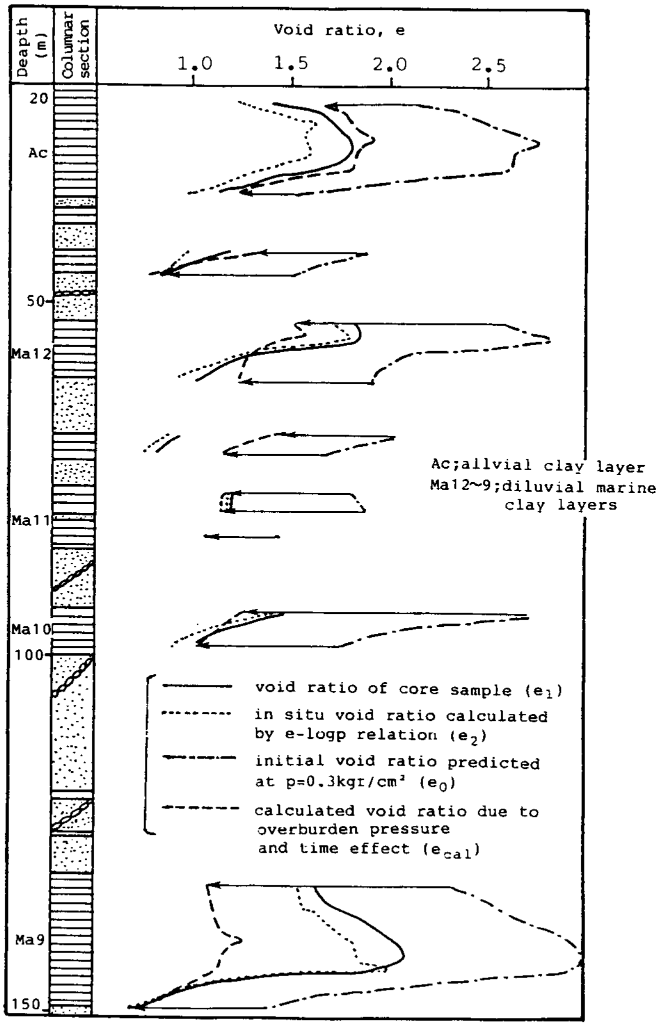

Fig. 11 Void ratio distribution with depth.

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