A UNIFIED CONCEPT OF e-LOG p RELATIONSHIP OF CLAYS

CONCEPT UNIFIE D'UN RAPPORT e-LOG p EN ARGILES

Takashi Tsuchida

Geotechnical Engineering Division
Port and Harbour Research Institute, Yokosuka, Japan

SYNOPSIS A unified concept of $e - \log p$ relationship of clays is newly proposed. When clays are consolidated one-dimensionally from the very large initial void ratio, each clay shows a unique "standard e-lop p curve", on which the logarithm of specific volume f (=1+e) and $\log p$ have a linear relationship. In case that natural clay has a structure due to the aging, the insitu void ratio e_0 can be larger than the void ratio given by the the standard $e - \log p$ curve, while the void ratio becomes smaller than what is given by the standard curve when the clay is disturbed during the process of sampling and consolidated in the laboratory. By consolidating the clay samples with the pressure much larger than the consolidation yield stress, the structure due to the aging is broken and the effect of the sample disturbance also disappears, and finally the e-$\log p$ relationship coincides with the "standard curve" determined by the liquid limit of clay.

INTRODUCTION

A number of studies has been carried out on the e-$\log p$ relationship of clays. An early study of Skempton (1944) showed the following fundamental findings on this topics;

a) the compressibility index C_c has a strong relationship with the liquid limit w_L.

b) the sample disturbance for natural clay and the initial water content for laboratory prepared clay have important effects on the e-$\log p$ relationship.

c) There are some discrepancy between the laboratory compression curve and the *sedimentation compression curve*, which is obtained by insitu void ratio and the overburden stress or the consolidation yield stress in the field.

Based on the work of Skempton and others, Terzaghi and Peck suggested the following equations applicable for virgin compression.

Remolded soil: $C_c = 0.007\,(w_L-10)$

Undisturbed soil: $C_c = 0.009\,(w_L-10)$

However, the above equations do not always give good estimation of C_c especially for undisturbed soils, and many empirical equations have been proposed for different soils. Recently it has been recognized that the mechanical properties of natural clay deposits are different from those of clays prepared in the laboratory. To explain the differences Burland (1990) proposed a concept of "intrinsic" properties of clay and the *intrinsic compression line*. In this study, the author proposes a unified concept on e-$\log p$ relationship of clay. This concept can cover a wide range of soils and the compressibility of both natural aged clays and laboratory prepared clays can be clearly explained. Finally, discussions are made on the difference between the author's concept and that of Burland.

EFFECT OF INITIAL VOID RATIO ON $e - \log p$ RELATIONSHIP OF LABORATORY PREPARED CLAYS

In the laboratory consolidation test, the initial void ratio of clay has a fundamental effect on $e - \log$ p relationship. Fig.1 shows $e - \log p$ curves of a soft marine clay whose initial void ratio e_0 are 1.1, 2.0, 3.2 and 4.0 times e_L, the void ratio at the liquid limit, respectively. As shown in Fig.1, the larger the initial void ratio e_0, the larger the compressibility of clay. It seems that the $e - \log p$ curves for the various initial void ratios are gradually converging into a unique curve, increasing the consolidation pressure. According to the consolidation test results, where the initial water contents are 5 - 8 times the liquid limit, it has been observed that the logarithm of specific volume f ($=1+e$), instead of void ratio e, showed the linear relationship to $\log p$ (Yano et al.,1988, Kobayashi et al.,1990). This tendency is also shown in Fig.1.

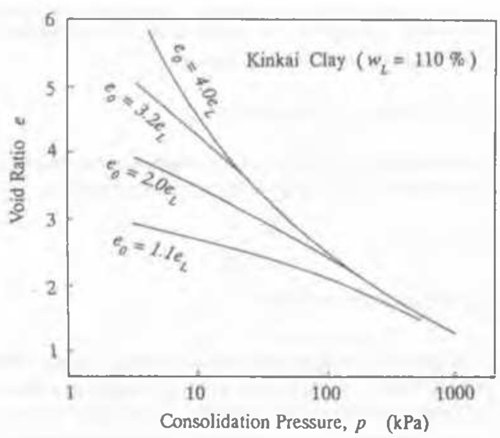

Fig.1 Effect of Initial Void Ratio on $e - \log p$ Curve

EFFECTS OF CLAY STRUCTURE AND SAMPLE DISTURBANCE ON $e - \log p$ RELATIONSHIP

Recently it was known that remolded clay samples having a structure due to the aging effect can be reproduced by consolidating clay slurry under high temperature condition (Tsuchida et al., 1991). Fig.2 shows the comparison of e-$\log p$ relationships of Osaka Bay Clays, including the remolded clay under high temperature (70°C, HT sample), the remolded clay consolidated with room temperature (RT sample) and the undisturbed sample with the same liquid limit and the consolidation yield stress p_c. As shown in Fig.2, HT sample and the undisturbed sample have slightly larger initial void ratios than RT sample, and they showed the largest compressibility, when the consolidation pressure p just exceeded the consolidation yield stress. While, when p became 3–5 times as much as p_c, e–log p relations of 3 samples tend to converge into a unique curve. These characteristics of e – log p curves can be explained as follows (Tsuchida, 1991):

1) In undisturbed samples and HT samples a structure was formed due to the effect of aging or bonding, while in RT samples the structure was not formed. The samples with the structure had larger void ratio in the initial stage than the samples without the structure.

2) When the consolidation pressure exceeds p_c, undisturbed samples and the HT samples showed the large compressibility, because the structure began to be broken. By consolidating at with pressure much larger than p_c, the effect of the structure disappeared and the e–log p relationships of 3 samples finally became almost the same.

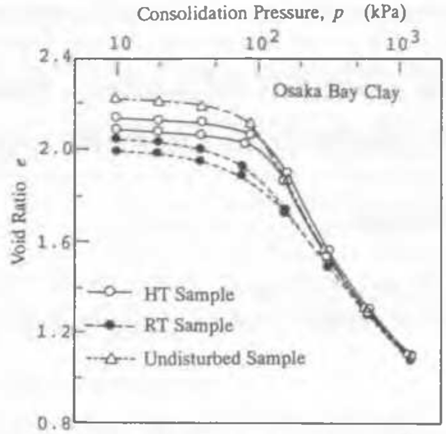

Fig.2 Effect of Structure on e – log p Curve

The effect of sample disturbance on e – log p curve was studied by Okumura (1974). Fig.3 is a reproduction of Okumura's data. As shown in Fig.3, the void ratio of heavily disturbed sample is smaller than that of sample with little disturbance, however, as consolidation pressure increases, the e – log p curves tend to converge into a unique curve. Although the effect of sample disturbance is almost contrary to that of the structure due to the aging, it is common that those effects gradually disappear as the consolidation pressure increases.

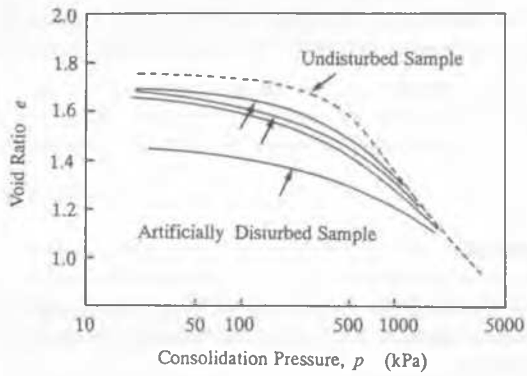

Fig.3 Effect of Sampling disturbance on e – log p Curve

A UNIFIED CONCEPT OF e–log p RELATIONSHIP of CLAY

According to the above considerations, a new concept of e–log p relationship is proposed. The fundamental assumptions of the concept is described as follows:

a) When a clay is consolidated one-dimensionally from a very high initial void ratio, it shows a "standard e–lop p curve" on which the logarithm of specific volume f (=1+e) and log p have the linear relationship (Butterfield, 1979).

b) The standard curve can be determined by the liquid limit w_L of clay.

c) In case that natural clay has a structure due to the aging, the initial void ratio e_0 can be larger than the value given by the standard curve, while, the void ratio becomes smaller than the value given by the standard curve, when the clay is disturbed during the process of sampling and is consolidated in the laboratory.

d) By consolidating the clay samples with the pressure much larger than the consolidation yield stress, the structure due to the aging is broken and the effect of the sample disturbance also disappears, and finally the e–log p relation coincides with the standard curve.

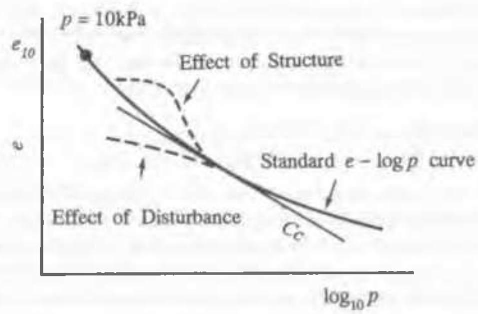

Fig.4 (a) Standard e – log p Relationship (e – log p system)

Fig.4(a) and Fig.4(b) illustrate the standard e – log p curve in the e – log p system and the log f – log p system, respectively. The standard e – log p curve can be described by the following equation;

$$\log_e (1+e) = -C(\log_{10} p - 1) + \log_e (1+e_{10}) \quad (1)$$

where e_{10} is a void ratio at p=10kPa on the standard curve, and C is a grade of standard curve (line) in Fig.4(b), and is indicated as follows:

$$C = C_c / (1+e) \quad (2)$$

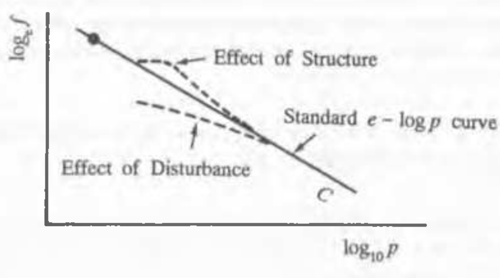

Fig.4 (b) Standard e – log p Relationship (log f – log p system)

ADAPTABILITY OF THE CONCEPT

To study the validity of the concept, the linearity of log f – log p relationship, which is observed when consolidation pressure is much larger than consolidation yield stress, is verified for a number of consolidation test data of marine clays. And using the linear part of log f – log p relationship, parameters C and e_{10} of equation (1) is determined by the regression analysis.

Fig.5(a) and Fig.5(b) show $C - w_L$ and $e_{10} - w_L$ relationships of Osaka Bay Clay, respectively. As shown in Fig.5, both C and e_{10} have good correlations with w_L. Therefore it can be said that the standard e–log p relationship of clay, on which the effects of structure or sample disturbance are eliminated, is determined by the liquid limit. Similar analyses were carried out using the data of Tokyo Bay Clay, Ariake Clay, Maizuru Clay, Kuwana Clay and Banjarmasin Clay (Indonesia), and all the data of $C - w_L$, $e_{10} - w_L$ relationships for 6 marine clays are summarized in Fig.6 and Fig.7. Fig.6 and Fig.7 indicate that the difference of the standard e – log p curve of , is not very large among these 6 marine clays. Regression analyses gave the following equations for C and e_{10}:

$$C = 0.0027\, w_L + 0.1 \qquad (3)$$

$$e_{10} = 0.042\,(w_L - 6) \qquad (4)$$

Although various empirical equations have been proposed on the relationship of C_c and w_L of natural clays, there is no relationship which can cover different kinds of clays. To consider the C_c–w_L relationship for natural clays, four important factors, consolidation pressure, initial void ratio, existence of structure due to the aging effect, sample disturbance, must be taken into consideration. The proposed standard e – log p curve is a relationship where the clay samples finally reach to with increasing the consolidation pressure, and the effects of the structure and the disturbance disappear on it. When we focus on this standard curve, the compressibility of clay can be described by the liquid limit fairly well. For example, the compressibility index C_{c1000} of the standard e–log p curves at p=1000 kPa were calculated using consolidation test data of 350 undisturbed clay sample in Osaka Bay and Tokyo Bay. As shown in Fig.8 (a) of $C_{c1000} - w_L$ relationship, C_{c1000} has a good correlation with the w_L. Fig.8(b) is the C_c–w_L relationship of Osaka Bay Clay and Tokyo Bay Clay in the conventional method, in which C_c is defined as the maximum value of de/d(log p) in e–log p curve. The correlation in Fig.8 (b) is not so good as shown in Fig.8 (a), because the conventional value of C_c includes the effects of above-mentioned four factors, which are variable in each undisturbed sample.

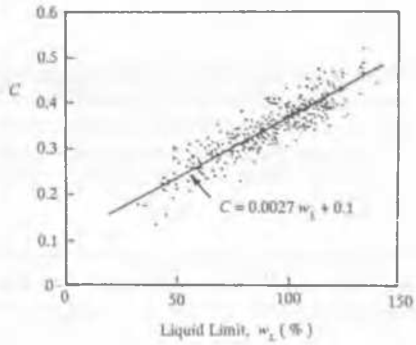

Fig.6 $C - w_L$ Relationship (6 marine clays)

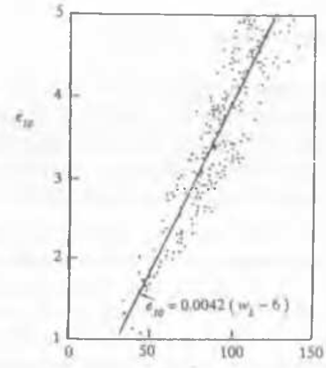

Fig.7 $e_{10} - w_L$ Relationship (6 marine clays)

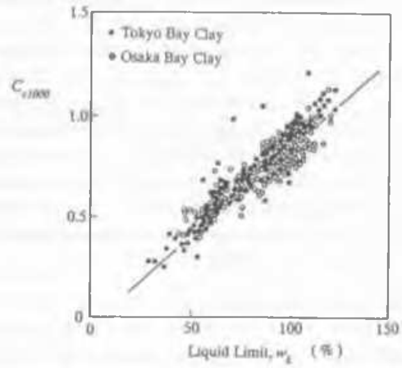

Fig.8 (a) $C_{c1000} - w_L$ Relationship

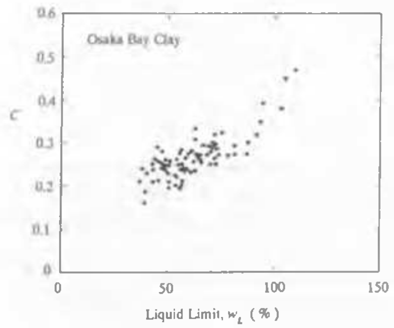

Fig.5 (a) $C - w_L$ Relationship (Osaka Bay Clay)

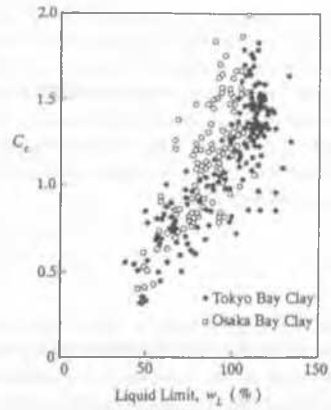

Fig.8 (b) $C_c - w_L$ Relationship

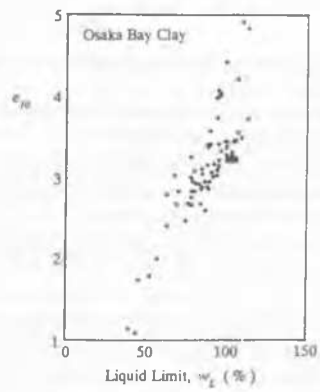

Fig.5 (b) $e_{10} - w_L$ Relationship (Osaka Bay Clay)

DISCUSSIONS

Burland (1990) recently proposed a concept of intrinsic properties of clay. By analyzing a number of laboratory consolidation test data of clays whose initial water content is 1.0 - 1.5 times the liquid limit, he found out that most of the $e - \log p$ relationship can be normalized by using the following parameters;

$$I_v = (e - e_{100}^*)/(e_{100}^* - e_{1000}^*) = (e - e_{100}^*)/C_c^* \quad (5)$$

where I_v is called void index and e_{100}^* and e_{1000}^* are void ratios when consolidation pressure are 100kPa and 1000kPa, respectively. C_c^* is defined as (e_{100}^* - e_{1000}^*). According to Burland, C_c^* and e_{100}^* is given as the following expressions:

$$C_c^* = 0.256\, e_L - 0.04 \quad (6)$$

$$e_{100}^* = 0.109 + 0.679 e_L - 0.089 e_L^2 + 0.016 e_L^3 \quad (7)$$

where e_L is a void ratio at the liquid limit.

Burland called the relationship between I_v and $\log p$ the *intrinsic compression line* (ICL) which is inherent to the clay and independent of its natural state. Burland further explained that the difference in $e - \log p$ relationship of natural clays from the ICL is due to the structure or the bond of natural clays.

The standard relationship proposed in this study is also independent of the structure and the sample disturbance of natural clay samples, and all $e - \log p$ curves finally converge into it. In this sense the standard relationship is an "intrinsic" property of clay. One of the question on ICL concept proposed by Burland is why the initial void ratio must be 1.0–1.5 times e_L for clays of ICL. As shown in Fig.1, another set of $e - \log p$ curves inherent to the clay can be easily produced in the laboratory when the initial void ratio is different, and there is no evidence that the initial void ratios of natural deposit are 1.0–1.5 times e_L. Fig.9 is the comparison between ICL and the standard $e - \log p$ relationships, which are given by equations (1), (3) and (4) and normalized by equations (5), (6) and (7). The normalized standard relationships, which are variable according to the liquid limit and have some variation around equations (3) and (4), are indicated as the shaded area. As shown in Fig.9, ICL is far below the zone of the standard relationships in most of the consolidation pressures. This is because the initial void ratio is so small in ICL samples as to converge into the standard relationship. In the author's opinion, Burland's ICL is an useful index for laboratory $e - \log p$ curves, but not an "intrinsic" property of clay, because there is no reasonable meaning to designate the initial void ratio as 1.0–1.5 times the liquid limit.

In Fig.9, the *sedimentation consolidation line* (SCL) proposed by Burland is also indicated. Most of SCL is included in the range of the standard $e - \log p$ relationships, which means that SCL can be explained only by the initial void ratio when the sedimentation started, and that the difference between ICL and SCL is not always due to the structure of natural clays. The void index I_v of the insitu Osaka Bay Clay calculated by equation (5) - (7) are plotted with the consolidation yield stress p_c in Fig.9. As the mechanical properties of Osaka Bay Clay has been studied in detail in relation to the Kansai International Airport project, it is known that the deep diluvial clay has a structure due to the aging. As shown in Fig.9, most of the data are plotted above the SCL, and some are plotted above the range of the standard relationships, when p_c is larger than 200 kPa. This result agrees well with the existence of the structure in the deep diluvial clay layers.

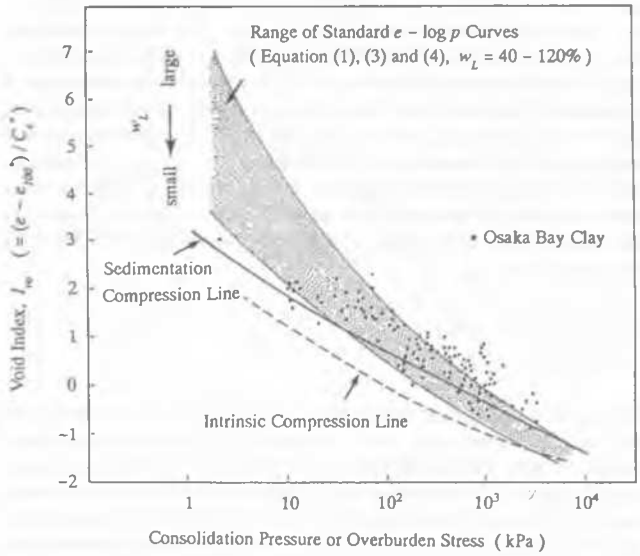

Fig.9 Standard $e - \log p$ relationship and ICL, SCL by Burland

CONCLUSIONS

An unified concept of $e - \log p$ relationship of clay is newly proposed. When clay is consolidated one-dimensionally from the very large initial void ratio condition, each clay shows an unique "standard e–lop p curve", on which the logarithm of specific volume f (=1+e) and $\log p$ have the linear relationship. In case that natural clay has a structure due to the aging, the insitu void ratio e_0 can be larger than the void ratio given by the the standard $e - \log p$ curve, while the void ratio becomes smaller than what is given by the standard curve when the clay is disturbed during the process of sampling and consolidated in the laboratory. By consolidating the clay samples with the pressure much larger than the consolidation yield stress, the structure due to the aging is broken and the effect of the sample disturbance also disappears, and finally the e-log p relationship coincides with the "standard curve" determined by the liquid limit of clay.

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