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COMPARISON OF CONSOLIDATION CURVES FOR REMOLDED MUD VOLCANO OF SIDOARJO, INDONESIA

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ABSTRACT: Sidoarjo mud volcano (Lusi) is one of the most challenging problems regarding to the compressibility of fine grained soils in Indonesia. Understanding about compressibility behavior is essential to construct appropriate remediation program for this problems. Consolidation test has been conducted to investigate the compressibility behavior of Lusi mud volcano. In this study, the laboratory test result is compared with estimated value derived from several empirical equations. A simple equation can be used to predict *e*-log σ' curve very well by using the correlation between initial void ratio (e_0) and void ratio corresponding to unit pressure (e_1); and correlation between compression index (C_c) and physical properties of soils, such as liquid limit (w_L) or natural water content (w_n). This equation predict better than other available equations in literature when compared with laboratory test of Lusi mud volcano.

Keywords: Compressibility Curve, Consolidation, Compression Index, Empirical Equations

1. INTRODUCTION

One of the most challenging problems regarding to the compressibility of fine grained soils in Indonesia is the eruption of mud volcano in Sidoarjo district, East of Java. This mud is known as Lusi. It has been erupted since May 2006 and still continues. The fresh erupted material is considered as high water content material which collected inside of 12 meters dike. Subsequently, this materials undergo sedimentation process and self-consolidation process, and it settled in about 640 ha area. Large amount of mud was produced and it becomes serious environmental issue in the future if not used appropriately. Appropriate remediation program need to be constructed to solve this problems and mostly required the knowledge of the compressibility behavior of this materials.

Compressibility behavior requires appropriate consideration when dealing with fine grained soils. Compression index (C_c) is one of the most important parameters that used to describe compressibility of fine grained soils. Compression index can be derived from two different ways: direct measurement by conducting laboratory test and calculation from available empirical equations. Oedometer and Rowe cell are two famous apparatuses generally used to determine compression index in laboratory. Since laboratory test requires undisturbed samples, the accuracy of this method relies on the quality of the specimens. Good quality of undisturbed specimens are difficult to be obtained. Sampling process, transportation process, and adjustment process in the apparatus may increase the disturbance degree of soil sample. Accuracy of laboratory equipment also plays important role in order to obtain reliable results. On the other hand, recently many equations are available in literature to calculate compression index based on physical properties. Physical properties of soils can be determined directly from laboratory test easily and require only disturbed samples. This method is considered to be easier to use compare with the direct measurement method. Furthermore, this method requires less cost and time compare with the other one.

This paper discuses compressibility curve of Lusi mud volcano. One-dimensional consolidation test using Oedometer apparatus was conducted in laboratory. The results of the test were plotted in void ratio (e) and vertical effective stress (σ') (in log scale). Estimation methods from available empirical equations were conducted and compared. The results were plotted together with the experimental results. Performance of those empirical equations are discussed.

2. AVAILABLE COMPRESSIBILITY EQUATIONS IN LITERATURE

Numerous empirical equations to estimate C_c are available in literature. The compression index of soils has been tried to be correlated with single variable of liquid limit (w_L) [1,2,3,4,5,6,7,8], plasticity index (I_P) [7,9,10,11], shrinkage index (I_S) [11], natural water content (w_n) [5,7,8,12,13,14,15], initial void ratio (e_0) [2,7,14,15,16,17,18], initial porosity (n_0) [19], dry density (γ_d) [15] and multivariable equations combining those previously mentioned indices

Table 1 Selected empirical equations to determine compression index (C_c)

Empirical equations	Applicability	References
Intrinsic variables (liquid limit (w_L))		
$0.007(w_L-10)$	Remolded clays	Skempton [1]
$0.0046(w_L-9)$	Brazilian clays	Cozzolino [2]
$0.017(w_L-20)$	All clays	Shouka [3]
$0.009(w_L-10)$	Normally consolidated clays	Terzaghi and Peck [4]
$0.006(w_L-9)$	All clays with wL < 100%	Azzouz et al. [5]
$(w_L-13)/109$	All clays	Mayne [6]
$0.011(w_L-6.36)$	Busan clays, Korea	Yoon et al. [7]
$0.0118(w_L-20.7)$	Silts and clays, Ireland	McCabe et al. [8]
State variables (natural water content (w_n))		
$0.01(w_n-5)$	All clays	Azzouz et al. [5]
$0.01\ w_n$	All clays	Koppula [12]
$0.01(w_n-7.549)$	All clays	Herrero [13]
$0.0115w_n$	Organic silts and clays	Bowles [14]
$0.01(w_n+2.83)$	Busan clay, Korea	Yoon et al. [7]
$0.008w_n-0.044$	Remolded Iranian soils	Abbasi et al. [15]
$0.014(w_n-22.7)$	Silts and clays, Ireland	McCabe et al. [8]

with other physical properties such as specific gravity (G_s)[5,7,12,15]. Physical properties of soils are classified into two groups, namely intrinsic properties and structural properties [15]. The intrinsic properties are then referred as intrinsic variables and the structural properties are the state variables [20]. The intrinsic variables consist of consistency limit (w_L, I_P and I_S). Those variables are influenced by mineralogy of soil particle and are independent from disturbance of specimen[15,20]. The state variables consist of w_n, e_0, n_0 and γ_d. Those variables are sensitive to specimen environment disturbance[15,20]. Liquid limit-based and natural water content-based empirical equation are reported to give better results compared than other indices. Table 1 presents some selected empirical equations to determine C_c available in literature.

Previously mentioned literature that propose estimation of C_c do not predict the void ratio-effective stress relationship (e-log σ'). They only predict the slope of the e-log σ' curve. The e-log σ' curve generally can be written linearly as in Eq. (1) where e_1 is the void ratio corresponding to effective vertical stress at unit pressure (e when σ'=1 kPa) and C_c is the slope of the curve. Once the e_1 can be determined, many different e-log σ' equations can be derived from different C_c equations.

$$e = e_1 - C_c \log \sigma' \tag{1}$$

Abbasi et al. [15] conducted test on 26 different Iranian remolded soils. Each specimen was prepared in three different density and

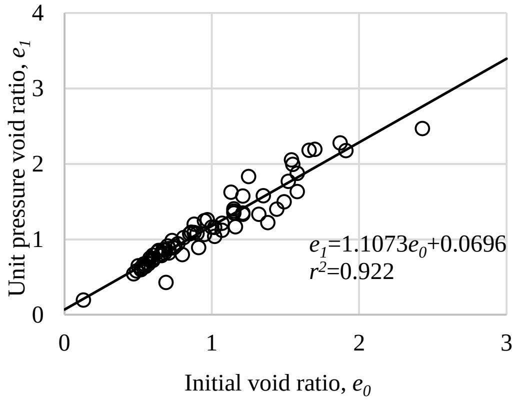

Fig. 1 Relationship between initial void ratio (e_0) and unit pressure void ratio (e_1) (data from Reference [15]).

subjected to one-dimensional consolidation test to obtain C_c. Based on the results, relationship between e_0 and e_1 can be obtained. Fig. 1 shows the plotted data of e_0 and e_1. The correlation between e_0 and e_1 is presented in Eq. (2) and it shows good correlation between e_0 and e_1, indicated from high coefficient of determination (r^2=0.922). Eq. (2) and one of the equation presented in Table 1 can be used to draw e-log σ' based on Eq. (1).

$$e_1 = 1.1073e_0 + 0.0696 \tag{2}$$

Abbasi et al. [15] proposed Eq. (3) and (4) based on experimental results to obtain e-log σ' equation in Eq. (5).

$$C_c = -0.461\gamma_d + 0.883 \tag{3}$$

$$e_1 = -1.78\gamma_d + 3.70 \quad (4)$$

$$e = (-1.78\gamma_d + 3.7) - (-0.461\gamma_d + 0.883)\log\sigma' \quad (5)$$

Berilgen et al. [21] proposed an empirical equation to satisfy the *A*, *Z* and *B* constants for *e*-log *σ'* equation proposed by Liu and Znidarcic [22] that presented in Eq. (6). *A*, *Z* and *B* are constants that depended on e_0, I_P and I_S. The equations to determine those constants are presented in Eq. (7),(8) and (9).

$$e = A(\sigma' + Z)^B \quad (5)$$

$$A = 2.69[\exp(0.008(I_P))] \quad (6)$$

$$B = (1 + e_0)[0.008\ln(I_P) - 0.054] \quad (7)$$

$$Z = (1 + e_0)\exp[1.97 - 3.9\ln(I_L)] \quad (8)$$

Tripathy and Mishra [23] proposed an *e*-log *σ'* equation based on Skempton's compression index equation as shown in Eq. (10); where I_v is intrinsic void index, C_c^* is intrinsic compression index and e_{100}^* is the void ratio corresponding to a vertical effective stress of 100 kPa. The equation to calculate C_c^* and e_{100}^* are presented in Eq. (10) and (11). Both constants are depended on void ratio at liquid limit (e_L). The I_v is depended on vertical effective stress (*σ'*) as presented on Eq. (13).

$$e = I_v C_c^* + e_{100}^* \quad (9)$$

$$C_c^* = 0.256e_L - 0.04 \quad (10)$$

$$e_{100}^* = 0.016e_L^3 - 0.089e_L^2 + 0.679e_L + 0.109 \quad (11)$$

$$I_v = 2.45 - 1.25\log\sigma' + 0.015(\log\sigma')^3 \quad (12)$$

3. METHODS

Lusi mud volcano was selected to assess the compressibility equations. Physical properties of Lusi mud volcano has been published [24]. Lusi mud volcano contains mostly of fine grained soils (84.47%) and classified as high plasticity silt (MH). It has G_s = 2.71, w_L =58.44%, w_P = 30.77%, w_S=22.27% and I_P 27.66%. One-dimensional consolidation test using oedometer apparatus was conducted to obtain compressibility behavior of lusi mud volcano. The initial water content is about 82% and corresponding to initial void ratio 2.22. The *e*-log *σ'* curve obtained from laboratory test is compared with estimated curve from several approaches.

4. RESULTS AND DISCUSSIONS

Equation (1) is used as basis equation to derive estimated *e*-log *σ'* curves. The e_1 can be obtained from Eq. (2) and C_c is estimated from w_L and w_n. These two indices have been selected to represent intrinsic variables group and state variables group. Both indices has been reported to have high correlation with C_c compare to other indices within their group [8,15,20]. Fig. 2 shows the estimated *e*-log *σ'* curves in which C_c is derived from liquid limit and Fig. 3 shows the similar thing but C_c is derived from natural water content. Based on Eq. (2), unit pressure void ratio, e_1, for Lusi mud volcano is estimated to be 2.53. Both Fig. 2 and Fig. 3 indicate that most of the estimated *e*-log *σ'* curves might have similar tangent value but some of them quite far from laboratory test results

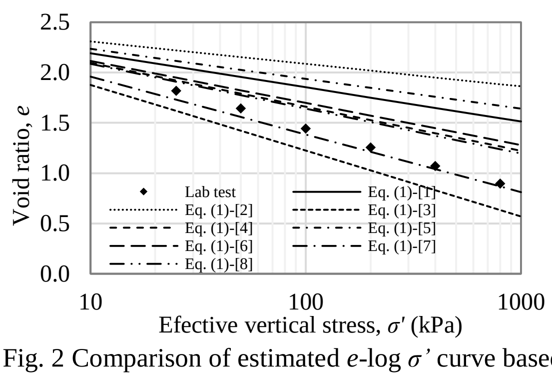

Fig. 2 Comparison of estimated *e*-log *σ'* curve based on Eq. (1) (e_1 from Eq. (2) and C_c from liquid limit-based equation) and oedometer test results

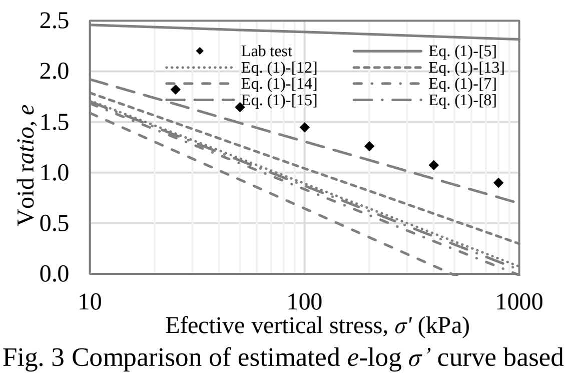

Fig. 3 Comparison of estimated *e*-log *σ'* curve based on Eq. (1) (e_1 from Eq. (2) and C_c from natural water content-based equation) and oedometer test results

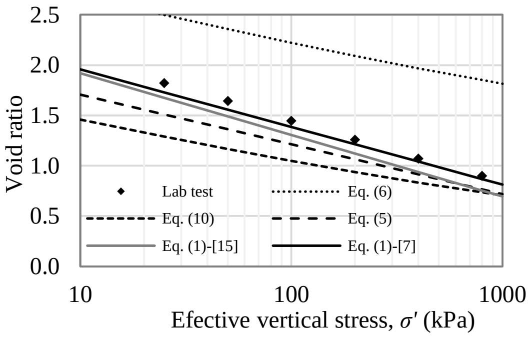

Fig. 4 Comparison of oedometer test results and estimated *e*-log *σ'* curve from different methods

plotted data. It is also indicated that *e*-log *σ'* curve from Yoon et al. [7] (Reffered as Eq. (1)-[7]) gives best prediction among group based on w_L to predict C_c and Abbasi et al. [15] (Reffered as Eq. (1)-[15]) gives best prediction among group based on w_n to predict C_c.

Performance of Eq. (1)-[7] and Eq. (1)-[15] equations are then compared with other method to generate *e*-log *σ'* curves from Abbasi approach (Eq. (5)), Berilgen approach (Eq. (6)), and Tripathy&Mesra approach (Eq. (10)). The comparison results are shown in Fig. 4. This figure indicates that *e*-log *σ'* curves derived from Eq. (1) shows the best prediction.

5. CONCLUSION

Compressibility behavior of Lusi mud volcano has been investigated from two different methods. Direct measurement from laboratory test using oedometer apparatus has been conducted. The result of test was compared with estimated *e*-log *σ'* curves. A simple equation (Eq. (1)) can predict e-log σ' very well by using the correlation between initial void ratio (e_0) and void ratio corresponding to unit pressure (σ'=1 kPa) (e_1) as presented in Eq. (2); and correlation between compression index (C_c) and physical properties of soils, such as liquid limit (w_L) or natural water content (w_n). This equation predict better than other available equations in literature when compared with laboratory test of Lusi mud volcano.

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