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UNDRAINED SHEAR STRENGTH OF SATURATED SOFT CLAY UNDER REPEATED IMPACT LOADING

Bing BAI[1], Weihua LI[2], Nan WU[3], Zhiguang GUO[4]

ABSTRACT

The method of improving saturated soft clay by both improving the drainage conditions using vertical drain and combining preloading method and dynamic compaction method has been used successfully. According to some typical laboratory test results, the concept of reconsolidation compression index is introduced. The definition of quasi-overconsolidation ratio is given, and furthermore, a model for predicting the undrained shear strength of saturated soft clay under repeated impact loading is suggested. In this model, the conditions of partial drainage and stages of impact are taken into account. The calculation results by the proposed model are in good accordance with the test data. Besides, the effect of disturbance consolidation on the undrained shear strength by this model is discussed.

Keywords: repeated impact loading; undrained shear strength; saturated soft clay

1. INTRODUCTION

In recent years, the method of improving saturated soft clay by both improving the drainage conditions using vertical drain and combining preloading method and dynamic compaction method has been used successfully in China. This method is named “dynamic drainage consolidation method” in the present paper (Bai 2006; Bai et al 2010; Bai and Shi 2017). However, the performance design and application of this method are still largely empirical in nature, relying heavily on the designer’s experience and judgment, and a pilot test is often carried out at the site to ascertain the operational parameters. For this reason, some field measurements were made recently, which mainly included the following aspects: pounder weight, drop height, number of drops per pass, number of passes, magnitude of pore pressure induced, rate of pore pressure dissipation, duration time between various passes, variation of bearing capacity, etc.

In order to give a reasonable explanation on the mechanism, the concepts of reconsolidation of saturated soft clay were developed (Bai and Shi 2017; Bai and Jiang 2017), and the reconsolidation deformation characteristics of saturated soft clay under repeated impact loading were studied by a large number of laboratory test results (Bai 2006). In these researches, the influences of drainage conditions on consolidation and reconsolidation are emphasized, and the variation of shear strength after impact loading was also investigated. In the present paper, combining some test results of reconsolidation volumetric strain by other researchers with author’s results, the relation between volumetric strain and pore pressure for some typical testing soils are analyzed, and the concept of reconsolidation compression index is introduced. Besides, a model for predicting the undrained shear strength of saturated soft clay under repeated impact loading is suggested. In the model, the conditions of partial drainage and stages of impact are taken into account.

[1]Professor, School of Civil Engineering, Beijing Jiaotong University, Beijing, China, bbai@bjtu.edu.cn
[2]Professor, School of Civil Engineering, Beijing Jiaotong University, Beijing, China, whli@bjtu.edu.cn
[3]Doctor, School of Civil Engineering, Beijing Jiaotong University, Beijing, China, 813778766@qq.com
[4]Doctor, School of Civil Engineering, Beijing Jiaotong University, Beijing, China, aguang7558@126.com

2. PARAMETERS OF RECONSOLIDATION VOLUME COMPRESSIBILITY

The reconsolidation deformation characteristics of saturated soft clay under repeated impact loading were studied systematically (Bai 2006; Bai and Jiang 2017). The clay sample used in experiments is disturbed Wuchang clay, of which physical properties are: plastic limit w_P =16.4%, liquid limit w_L=36.9%, plasticity index Ip=20.5, water content w=37.4%.
A reconsolidation index is defined, which shows the change of void ratio due to the change of effective stress, and can be expressed by

$$C_{rc} = \frac{-\Delta e}{\log \sigma'_{3c} - \log(\sigma'_{3c} - u)} = \frac{\Delta e}{\log(1 - \frac{u}{\sigma'_{3c}})} \quad (1)$$

where C_{rc} is reconsolidation index, u is the residual excess pore pressure generated by impact, σ'_{3c} is the effective confining pressure, and Δe is the change of void ratio after the dissipation of pore pressure.
It can be seen from Figure 1 that, reconsolidation index (C_{rc}) decreases with increasing the excess pore pressure (u/σ'_{3c}), and can be expressed by

$$C_{rc} = (6 - 2\frac{u}{\sigma'_{3c}}) \times 10^{-2} \quad (2)$$

As for C_{rc}, we can define a parameter $\alpha = C_{rc}/C_r$ with C_r being the swelling-recompression index (Bai and Shi 2017). Yasuhara and Andersen (1994) gave α =1.5 for Drammen clay by cyclic direct simple shear tests. Other researches (Ohara and Matsuda 1998; Hyodo 1992) thought that C_{rc} is in the range between C_r and C_c for remolded Kaolin clay by similar tests. The present tests show α=1.32, and further conclude that, the values of α should be dependent mainly on the plastic index and the particle structure of clay, and is independent on the types of dynamic loading.

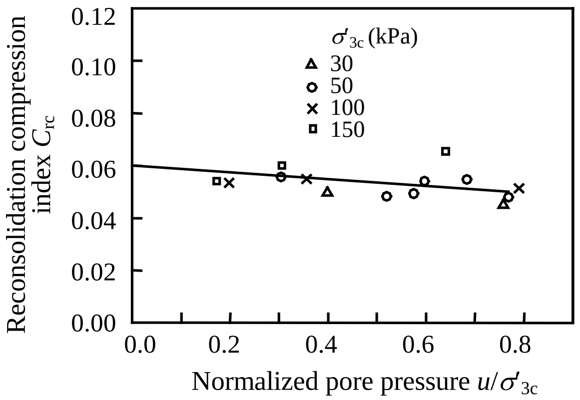

Figure 1. Relation between C_{rc} and u/σ'_{3c}

3. MODEL FOR PREDICTING UNDRAINED SHEAR STRENGTH

The normally consolidated soft clay undergoing impact loading or thermal loading often shows a quasi-overconsolidation state (Hyodo et al. 1992; Bai 2006; Bai and Shi 2017). Thus, a quasi-overconsolidation ratio can be defined as:

$$n_q = p'_N / p' \quad (3)$$

where p' is the effective stress of the point discussed, p'_N is the effective stress corresponding to the point of normal consolidation line with the same void ratio.

Figure 2 gives the change of stress state under several stages of impact loading and partially drained condition. After the former stage impact loading and partially drainage, the next stage impact loading is immediately applied. Now, we define a concept of dissipation ratio of pore water pressure, α_j (j=1, 2, 3, ...), which is the ratio of dissipated pore pressure to the total pore pressure before dissipation (Bai et al. 2017; Bai et al 2018).

Under the first stage impacting and partially drained, the corresponding stress state is D_1. The effective confining pressure of this point can be written as $p'_{D_1} = p'_i - (1-\alpha_1)\Delta u_1$. According to $\Delta e_{B_1 D_1} = \Delta e_{AA_1}$, we can obtain

$$C_{rc1}\{\log[p'_i - (1-\alpha_1 \Delta u_1)] - \log(p'_i - \Delta u_1)\} = C_c[\log p'_{A_1} - \log p'_i] \quad (4)$$

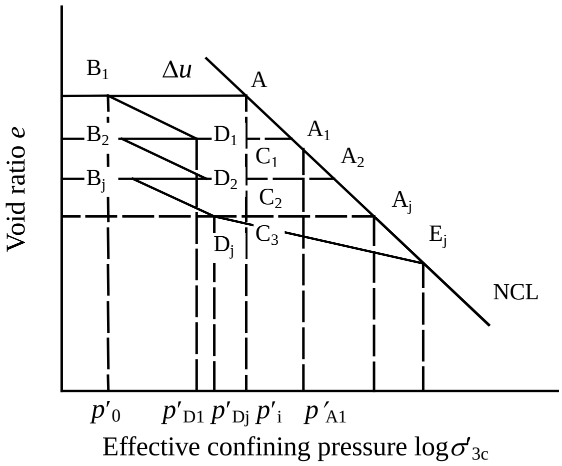

Figure 2. Condition under several stages of impacting and partially drainage

Using Equation 4 and assuming $\lambda'_1 = C_{rc1}/C_c$, the effective stress of normal consolidation line corresponding to D_1 can be expressed by

$$p'_{A_1} = p'_i \left[\frac{1-(1-\alpha_1)\Delta u_1 / p'_i}{1-\Delta u_1 / p'_i}\right]^{\lambda'_1} \quad (5)$$

The effective stress on normal consolidation line corresponding to D_2 after second impact loading can be expressed by (where $\lambda'_2 = C_{rc2}/C_c$)

$$p'_{A_2} = p'_{A_1}\left[\frac{1-(1-\alpha_1)\Delta u_2 / p'_i}{1-\Delta u_2 / p'_i}\right]^{\lambda'_2} = p'_j \cdot \left[\frac{1-(1-\alpha_1)\Delta u_1 / p'_i}{1-\Delta u_1 / p'_i}\right]^{\lambda'_1}\left[\frac{1-(1-\alpha_2)\Delta u_2 / p'_i}{1-\Delta u_2 / p'_i}\right]^{\lambda'_2} \quad (6)$$

Similarly, the effective stress on normal consolidation line corresponding to D_j after stage j impact loading is

$$p'_{A_j} = p'_i \prod_{k=1}^{j}\left[\frac{1-(1-\alpha_k)\Delta u_k / p'_i}{1-\Delta u_k / p'_i}\right]^{\lambda'_k} \ (j=1,2,3,\ldots) \quad (7)$$

where Δu_k is the total pore pressure after stage j impact loading, α_j is the dissipation ratio of pore

pressure after stage j impact loading, $\lambda_k' = C_{rck} / C_c$ and C_{rck} is the reconsolidation compression index after stage j impact loading, Π is the symbol which denotes product.
According to $\Delta e_{D_j E_j} = \Delta e_{A_j E_j}$, we can obtain

$$C_s(\log p'_{E_j} - \log p'_{D_j}) = C_c(\log p'_{E_j} - \log p'_{A_j}) \tag{8}$$

or

$$p'_{E_j} = \frac{(p'_{D_j})^{\lambda/(\lambda-1)}}{(p'_{A_j})^{1/(\lambda-1)}} \tag{9}$$

The overconsolidation ratio of state point D_j can be written as $OCR = p'_{E_j} / p'_{D_j}$, thus the following equation can be got:

$$\frac{c_{uD_j}}{c_{ui}} = \frac{c_{uD_j}}{c_{uE_j}} \cdot \frac{c_{uE_j}}{c_{ui}} = (OCR)^{\Lambda_0 - 1} \cdot \frac{p'_{E_j}}{p'_i} \tag{10}$$

When the pore pressure is dissipated completely after stage j impact loading, we have $\alpha_j = 1$ and $p'_{D_j} = p'_i$ from Figure 2. Using Equation 10, the following equation can be got:

$$\frac{c_{uD_j}}{c_{ui}} = (OCR)^{\Lambda_0 - 1} \cdot \frac{p'_{E_j}}{p'_{D_j}} = (OCR)^{\Lambda_0} \tag{11}$$

The above equation is just the prediction calculation formula of undrained shear strength under partially drained condition. Obviously, when $\alpha_k = 1$ (k=1, 2, … j), Equation 11 becomes the prediction calculation formula of undrained shear strength under several stages of impacting and fully drained condition.
Now, we give the calculation formula of undrained shear strength at state point B_2, … B_j in Figure 2. Previously, Bai (2016) proposed a calculation method for the shear strength under undrained impact loading, or:

$$\frac{c_{uB}}{c_{ui}} = n_{qB}^{\left(\frac{\Lambda_0}{1 - C_s / C_c} - 1\right)} = \left(\frac{1}{1 - \Delta u / p'_i}\right)^{\left(\frac{\Lambda_0}{1-\lambda} - 1\right)} \tag{12}$$

where C_c is compression index, C_s is swelling index, Λ_0 is an experimental parameter, n_{qB} is the quasi-overconsolidation ratio of state point B and can be written by $n_{qB} = p'_i / p'_0 = p'_i / (p'_i - \Delta u)$, $\lambda = C_s / C_c$.
Using Equation 12 and regarding $\Delta u = p'_{A_{j-1}} - p'_i - \Delta u_j$, we can get the following calculation equation only by replacing c_{uB}, c_{ui}, p'_i with c_{uB_j}, $c_{uA_{j-1}}$, $p'_{A_{j-1}}$:

$$\frac{c_{uB_j}}{c_{uA_{j-1}}} = \left[\frac{p'_{A_{j-1}}}{p'_i - \Delta u_j}\right]^{\left(\frac{\Lambda_0}{1-\lambda} - 1\right)} \tag{13}$$

and furthermore

$$\frac{c_{uB_j}}{c_{ui}} = \frac{c_{uA_{j-1}}}{c_{ui}} \cdot \frac{c_{uB_j}}{c_{uA_{j-1}}} = \frac{p'_{A_{j-1}}}{p'_i} \cdot \left[\frac{p'_{A_{j-1}}}{p'_i - \Delta u_j} \right]^{\left(\frac{\Lambda_0}{1-\lambda}-1\right)} \tag{14}$$

where $p'_{A_{j-1}}$ can be calculated by Equation 7, Δu_j is the increment of pore water pressure under stage j impact loading.

4. VERIFICATION OF THE PROPOSED MODEL

According to the laboratory test results (Bai 2006), we can obtain C_c=0.148, C_s=0.025, $\lambda=C_s/C_c$=0.169, Λ_0=0.76. Figure 3 gives the predicted results of undrained shear strength after the first stage impacting and reconsolidation by the proposed method. In the meantime, the predicted results by Yasuhara's formula (1994) have also been given. It can be seen from Figure 3 that the predicted results by the proposed method are higher than that of Yasuhara's formula in values, which is due to $C_{rc}>C_s$ in the above two calculating formulas.

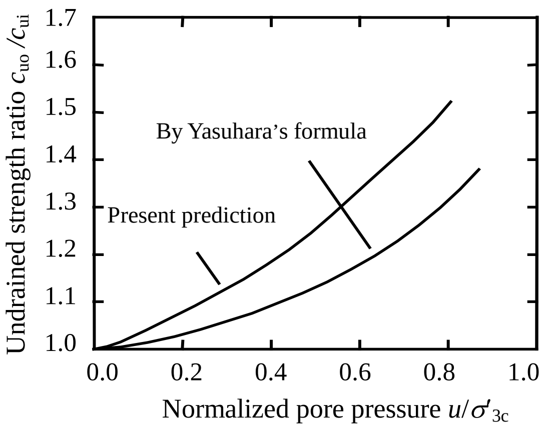

Figure 3. Predicted shear strength under the first stage of impact and reconsolidation

Table 1. Comparison of predicted undrained shear strength with measured one.

Sample number	**B-2**	**B-7**	**B-8**	**B-9**	**B-11**	**B-22**	**B-12**	**B-18**	**B-21**	**B-3**	**B-20**	**B-4**	**B-19**
Confining pressure σ'_{3c} (kPa)	50	50	50	50	50	50	30	30	30	100	100	150	150
Measured shear Strength c_{uo}/c_{ui}	1.67	2.25	1.72	2.11	2.19	2.33	1.96	2.29	1.96	1.55	2.57	1.47	1.85
Predicted shear Strength c_{uo}/c_{ui}	1.95	2.74	1.91	2.00	2.10	2.24	2.21	2,74	2.15	1.52	2.62	1.39	1.89
Relative error (%)	16.8	21.8	11.0	–4.8	–0.4	–10.4	12.5	16.4	8.8	–2.0	1.9	–5.7	5.5
Accumulated pore Ressure $\Delta u_{total}/\sigma'_{3c}$	1.55	2.50	1.50	1.57	1.68	1.70	1.75	2.21	1.67	1.04	1.94	0.83	1.41

According to Figure 3, the undrained shear strength that undergo the disturbance of impact loads

(where axial strain ε_a=0.2%, u/σ'_{3c}=0.2) and reconsolidation is the 1.1 times of that of the sample before impacting, which shows the implication of disturbance consolidation effect.
Table 1 gives the comparison of the predicted undrained shear strength with the measured one under several stages of repeated impact loading and fully drained condition. The test results contain various confining pressures (σ'_{3c}=30, 50, l00, 150kPa,) various impact loading, various numbers of impact and various stages of impact. The accumulated residual pore pressures ($\Delta u_{total}=\Delta u_1+\Delta u_2+\Delta u_3+\ldots$) are also given in Table 1. It can be seen from Table 1 that the calculation results by the proposed model are in good accordance with the test data.

5. CONCLUSIONS

The main results are summarized as follow:
(1) A model for predicting the undrained shear strength of saturated soft clay under repeated impact loading is suggested. The calculation results by the proposed model are in good accordance with the test data.
(2) The concept of reconsolidation compression index is introduced, and some important factors such as confining pressures, stages of impact and dissipation ratio of pore water pressure, etc. are also included.
(3) The predicted results also show that undrained repeated impact loading with drained rest periods may make normally consolidated clay more resistant to subsequent undrained cyclic loading.
(4) The effect of disturbance consolidation on the undrained shear strength of saturated soft clay by this model is discussed.

6. ACKNOWLEDGMENTS

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