Evaluation of Consolidation Coefficient of Non-standard Dissipation Types of Soil-Bentonite Wall Based on CPTU

Lulu Liu[1] Primary author
Institute of Geotechnical Engineering, Southeast University, Nanjing, China 211189;
believeliululu@163.com
Wenzong Gong[2]
Guangxi Communications Design Group CO., LTD, Nanning, China 530007;
rowley.nju@gmail.com
Guojun Cai[3] Corresponding author
Institute of Geotechnical Engineering, Southeast University, Nanjing, China 211189;
focuscai@163.com
Xuepeng Li[4]
Institute of Geotechnical Engineering, Southeast University, Nanjing, China 211189;
65052440@qq.com
Songyu Liu[5]
Institute of Geotechnical Engineering, Southeast University, Nanjing, China 211189;
liusy@seu.edu.cn

ABSTRACT: To evaluate the consolidation coefficient of non-standard dissipation types of soil-bentonite wall, the pore pressure cone penetration test (CPTU) were conducted in field and the data were analyzed in detail using different evaluation methods. The results show that the consolidation coefficient evaluated by the time square root method is close to that by the time logarithm method, but the result of the modified t_{50m} method is relatively large. When the dissipation time of non-standard dissipation type is less than t_{50m}, the time square root method proposed by Sully can be used to predict the time t_{50m} value of half of the excess pore pressure dissipation, which can shorten the CPTU test duration. Admittedly, the time logarithm method is a simplification in pore pressure dissipation curve.

Keywords: CPTU; soil-bentonite; non-standard dissipation; consolidation coefficient

1 Introduction

With the rapid growth of population and the acceleration of industrialization and urbanization, China can produce about 1.2 ×10^8 tons of municipal solid waste per year, and the increasing speed is faster. For these municipal solid wastes, there are fewer measures to deal with the effect. The harmless treatment rate is only 2.3%, and most of the municipal solid waste is the same. Transport to the suburbs is piled up in the open air, which makes more than 200 cities in China trapped in garbage surrounded, so garbage disposal and pollution prevention has become a more prominent problem of environmental protection [1]. Landfill is the main disposal method of municipal solid waste in China. With the rapid growth of the amount of municipal solid waste clearance and transportation in China, the height of the landfill refuse heap is constantly increasing [2]. In the process of landfill, a large number of toxic and harmful substances are often mixed with various kinds of garbage and then landfill, which is equivalent to the concentration of a variety of harmful components, coupled with rain, fermentation and scouring, will inevitably produce more harmful leachate. If the anti-seepage ability of landfill is poor, landfill leachate will cause serious harm to the surrounding surface water and soil. In the treatment of leachate, the most direct and effective control method is to establish a perfect anti-seepage system, which strictly controls harmful pollutants, especially leachate, in a certain unit, and at the same time establishes a complete leachate treatment facility.

At present, cement grouting curtain (plastic concrete or cement-soil) is mostly used to prevent leachate diffusion in landfills in China. In contrast, the soil-bentonite wall has the advantages of strong impermeability, low cost and short construction period. D'appolonia [3], Evans [4] and Schneider [5] summarized the technology of bentonite wall. Compared with the cement-bentonite vertical wall, the bentonite vertical wall has the advantages of low permeability coefficient and good wall uniformity. In addition, the use of bentonite wall avoids the use of large quantities of cement, which conforms to the environmental protection policy of CO_2 emission reduction.

Research progress and application of soil-bentonite barrier in China lag behind those in Europe and America. The mechanism that causes the sudden change of engineering properties and poor retardation performance of soil bentonite materials, as well as the research on the evaluation method of compression and anti-seepage performance of soil bentonite wall for pollutants, are still lacking, and a relatively complete theory and technology for anti-seepage of landfill leachate has not yet been formed [6, 7,12-15]. This paper studies the consolidation coefficient of soil-bentonite wall with non-standard dissipation based on CPTU, and analyses the main mechanism of non-standard dissipation of pore pressure. Aiming at non-standard dissipation types, the time square root method and time logarithm method of Chai et al. [8], Sully et al. [9] are used to evaluate the consolidation of soil-bentonite wall. Finally, the consolidation coefficients of soil-bentonite wall evaluated by these methods are compared and analyzed.

2 Site Introduction and Testing Equipment

The test site is located in a landfill site in Jingjiang, Jiangsu province, China. A test project of soil-bentonite wall with a length of 15 m, width of 0.6 m and depth of about 10 m was built outside the landfill site. The bentonite used for the isolation wall is GMZ natural bentonite and the base soil is topsoil of 0 to 1 m below the surface near the site excavated isolation wall. Bentonite is Na-bentonite and backfill soil is sandy clay. Content of bentonite is 5% and backfill soil is 95%.

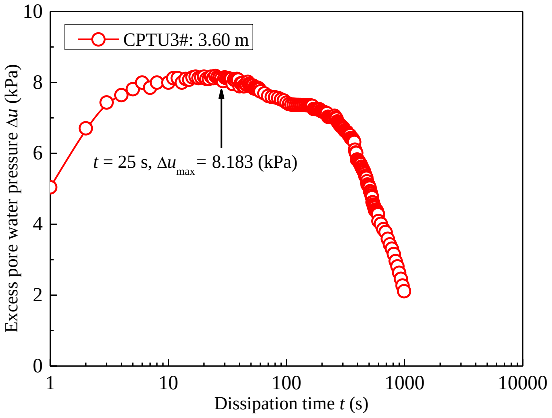
The test equipment is the static penetration (CPTU) test system, which is equipped with the latest multi-function digital probe. The probe has a cone angle of 60°, the diameter of the cone bottom is 35.7 mm, the cross-sectional area of the cone bottom is 10 cm^2, the surface area of the side wall friction cylinder is 150 cm^2, the thickness of the hole pressure test element is 5 mm and it is located at the cone shoulder. Figure 1 shows the CPTU field test of the soil-bentonite wall. To analyze the effect of adding bentonite, the CPTU probe penetrated not only into the soil-bentonite wall, but also into the foundation soil 1 m outside the wall. The test system mainly consists of penetration system, data acquisition system and data analysis system. Figure 2 shows the landfill and soil-bentonite wall used in the test. The water table is 1 to 2 m below the surface.

Figure 1 CPTU field test diagram of soil-bentonite wall

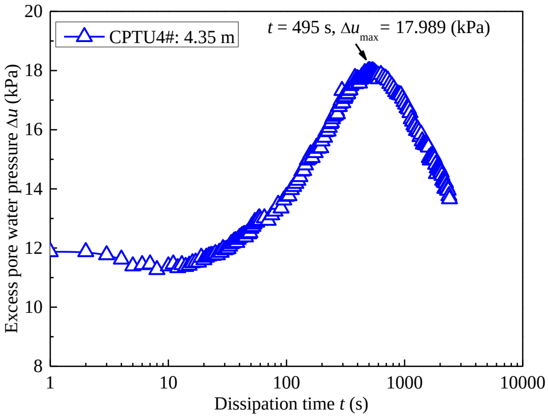
Figure 2 Landfill and soil-bentonite wall

3 Evaluation of consolidation coefficient of nonstandard dissipation type

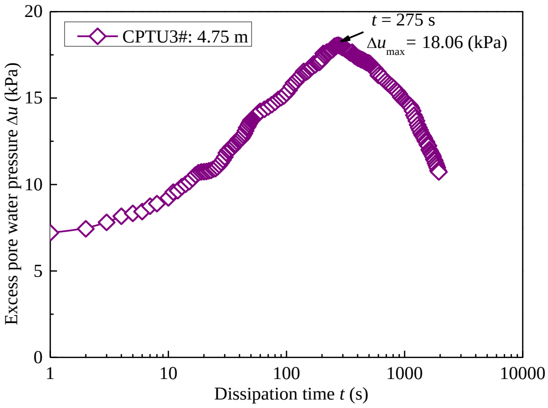
Figure 3 shows the non-standard dissipation pattern of the bentonite wall and the excess pore pressure dissipation pattern. The pore pressure dissipation curves at the depths of 3.60 m, 4.35 m, 4.75 m, 5.50 m, 7.10 m and 9.55 m are listed. In Figure 3, the maximum pore pressure caused by probe penetration is 8.183 kPa, 17.989 kPa, 18.06 kPa, 13.367 kPa, 16.371 kPa and 7.969 kPa, respectively. For the dissipation time, it is 25 s, 495 s, 275 s, 265 s, 305 s and 95 s. Experiments show that the excess pore pressure values of the standard dissipation tests in this area have the same characteristics, that is, the excess pore pressure values do not decrease immediately, but rise for a period of time to the maximum excess pore pressure, then begin to decrease with time, and finally dissipate. The dissipation time is more than 50% of the excess pore pressure dissipation time.



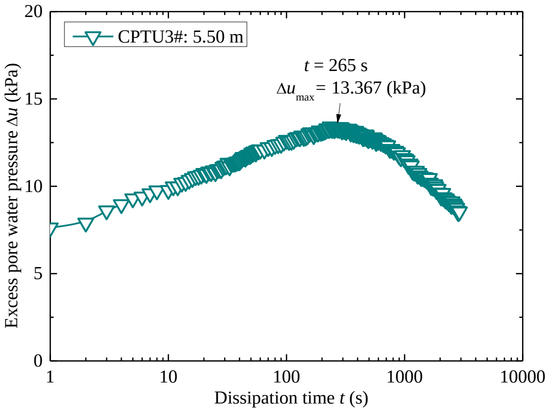
(a) At a depth of 3.60 m



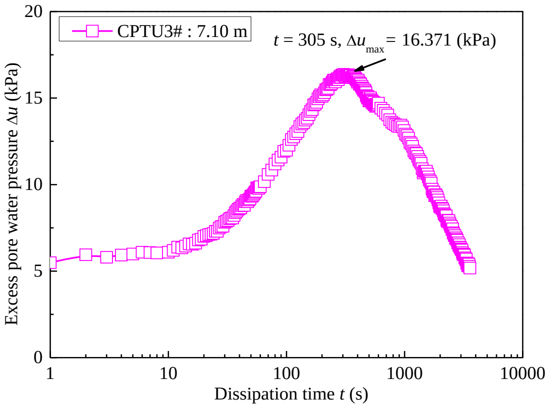
(b) At a depth of 4.35 m



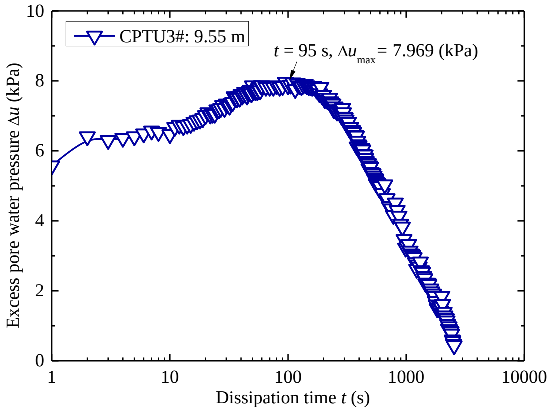
(c) At a depth of 4.75 m



(d) At a depth of 5.50 m



(e) At a depth of 7.10 m



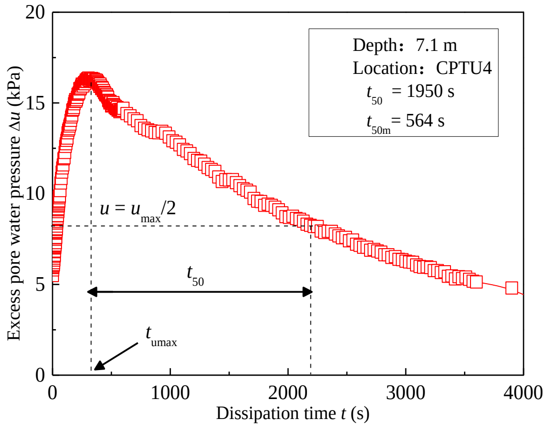
(f) At a depth of 9.55 m

Figure 3 Non-standard dissipation diagram of excess pore pressure of soil-bentonite wall

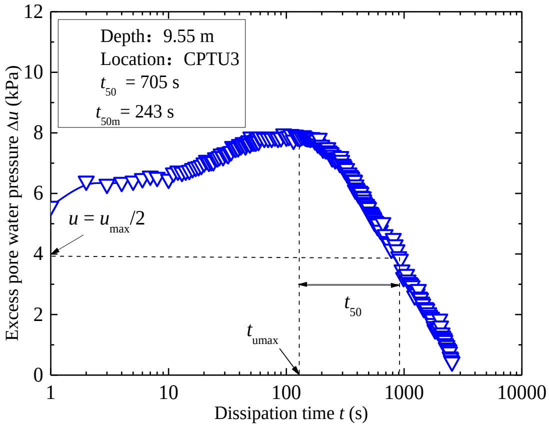
After knowing the non-standard dissipation diagram of excess pore pressure, three methods can be used to evaluate the consolidation coefficient of soil-bentonite wall, which are modified t_{50m} method, time square root method and time logarithm method [16].

3.1 Modified t_{50m} method

Among all non-standard pore pressure dissipation curves, two of them are illustrated as examples. Figure 4 shows the dissipation curve of excess pore water pressure at 7.1 m in CPTU4. If the standard dissipation method is used in the non-standard dissipation type, the consolidation coefficient can be evaluated by the t_{50} value shown in Figure 4 [16]. That is to say, the initial excess pore pressure is approximated to the maximum $u_{\max}$, the initial time is approximated to t_{umax}, and then the dissipation time of 50% of excess pore pressure is regarded as t_{50}. This approximation method undoubtedly brings some errors to the calculation results. In this test, the modified t_{50} is used to replace the t_{50} value, which makes the calculation result closer to the engineering practice. As shown in Figure 4, the t_{50} at 7.1 m in CPTU4 is 1950 s, and the revised t_{50} is 564 s, much smaller than the revised t_{50}.



(a) At a depth of 7.10 m



(b) At a depth of 9.55 m

Figure 4 Dissipation curve of excess pore water pressure

Figure 5 shows the t_{50} and the revised t_{50m} values based on CPTU tests. It can be seen from the figure that the t_{50}/t_{50m} value of Jingjiang soil-bentonite wall is 1.9-3.5, and the t_{50}/t_{50m} value of Chai et al [8] in a clay site in Japan is 2.6-8.8. Considering the different soil properties, the difference between the two results is acceptable.

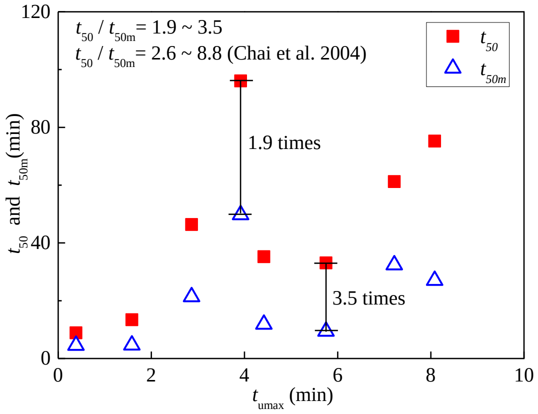


Figure 5 t_{50} and revised t_{50m} based on CPTU

Figure 6 shows the relationship between consolidation coefficient c_h and t_{50m} of soil-bentonite wall. Among them, the t_{50m} value is 9.4-33.1 min and the consolidation coefficient is 0.11-0.96 cm^2/min. At the same time, the results of Chai [8] based on numerical analysis are given. The t_{50m} value is 1.65-16.78 min and the consolidation coefficient is 0.33-3.33 cm^2/min. It is worth noting that Chai et al. [8] studied over-consolidated clay, and the material of soil-bentonite studied in this paper is under-consolidated or normal consolidation.

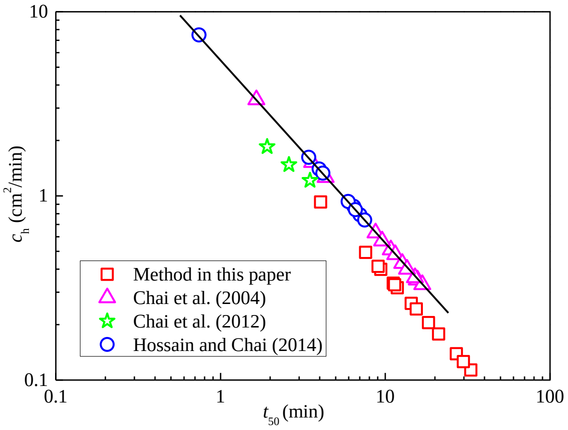


Figure 6 Evaluation of Consolidation Coefficient by Modified t_{50m} Method Based on CPTU

3.2 Time square root method

The time square root method is a new method for evaluating consolidation coefficient proposed by Sully in 1999 for the study of non-standard dissipation types of pore pressure [16]. The method for evaluating initial pore pressure is Sully's time square root-based regression method (Figure 7). The pore pressure dissipation curves of two different depths under the surface are illustrated as examples. As shown in Figure 8, the initial pore pressure u_i calculated linearly at 7.1 m depth in CPTU test hole is 72.7 kPa. The excess pore pressure (Δu = 21.7 kPa) can be obtained by subtracting the initial pore pressure u_o (u_o = 51 kPa) from the hydrostatic pressure u_o (u_o = 51 kPa). Half of the excess pore pressure dissipation, i.e. the corresponding $\sqrt{t_{50}}$ of 10.8 kPa, is 33.8$\sqrt{s}$, and the corresponding t_{50} is 1142 s. Similarly, the initial pore pressure u_i estimated linearly at the depth of 5.5 m in the CPTU test hole is 60.8 kPa. The excess pore pressure (Δu = 15.8 kPa) can be obtained by subtracting the initial pore pressure u_o (u_o = 45 kPa) and the corresponding $\sqrt{t_{50}}$ of 7.9 kPa is 52.5$\sqrt{s}$, and the corresponding t_{50} is 275 s. In the evaluation of the consolidation coefficient of soil-bentonite wall based on the time square root method, it is the key to approximate the data of pore pressure drop as a straight line, and then extend the straight line in reverse to obtain the initial pore pressure, which is an important conclusion that Sully obtained through the study of non-standard pore pressure dissipation curve in 1999.

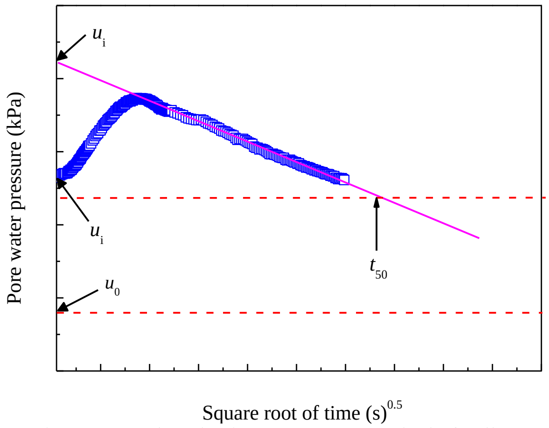
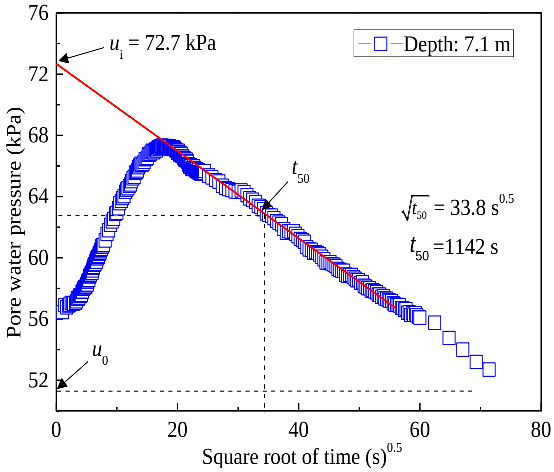
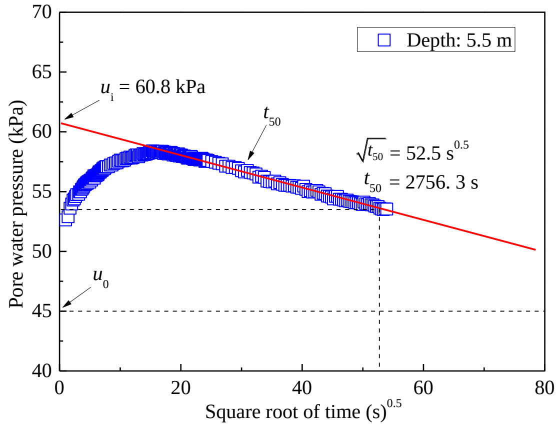


Figure 7 Based on the time square root method of Sully [9]



(a) At a depth of 7.1 m



(b) At a depth of 5.5 m

Figure 8 Time square root method based on Sully [9]

In this paper, the time square root method based on Sully et al. [9] is given to calculate the t_{50} value of soil-bentonite wall in the non-standard dissipation type. It is noteworthy that the dissipation time of the above dissipation test is greater than t_{50} value. So, if the dissipation time of CPTU test is less than t_{50} value, is it suitable to continue using the time square root method?

Figure 9 shows the process of data analysis with dissipation time less than t_{50} at a depth of 4.35 m. The approximate value of t_{50} ($\sqrt{t_{50}}$ is 62.1$\sqrt{s}$, and the corresponding value of t_{50} is 3856 s). That is to say, the time square root method based on Sully can be used in CPTU experiments when the dissipation time is less than t_{50}.

Figure 10 shows the relationship between the consolidation coefficient c_h and t_{50} of clay-bentonite isolation material based on Sully's time square root method. Among them, the value of t_{50} is 8.6-64.3 min and the coefficient of consolidation is 0.01-0.087 cm^2/min. At the same time, the graph gives Sully's research results based on time square root method. The stiffness index of soil is 50 and 500, respectively.

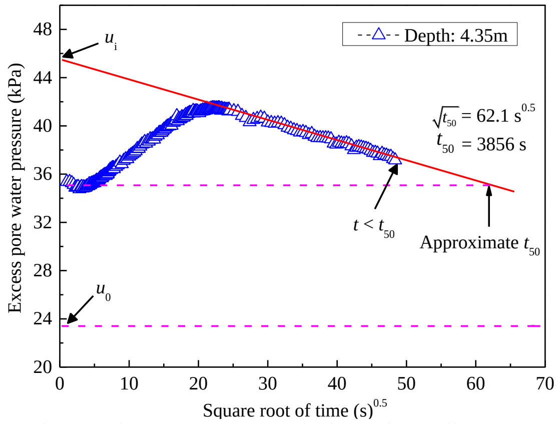


Figure 9 Time Square Root Method Based on Sully ($t < t_{50}$)

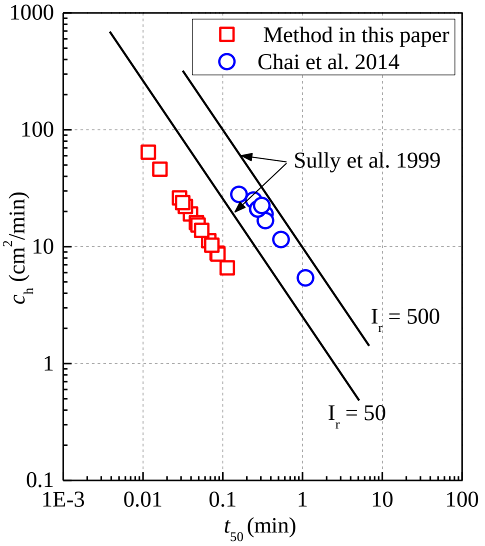
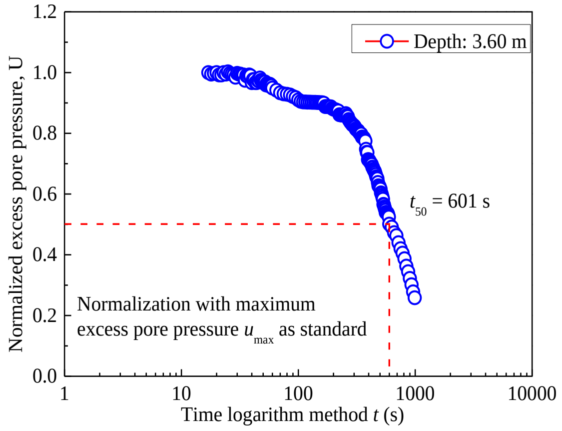


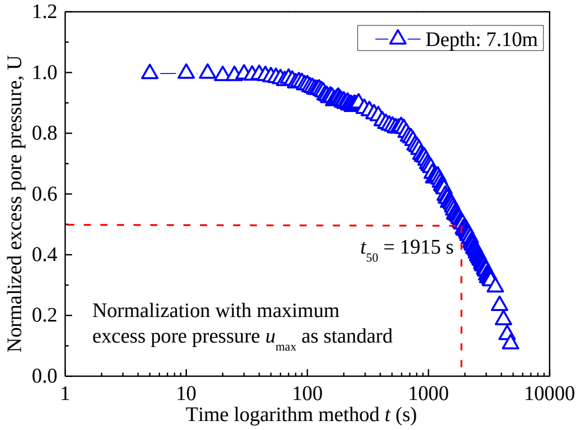
Figure 10 Evaluating the consolidation coefficient of soil-bentonite wall based on Sully's Time Square Root method

3.3 Time logarithm method

Figure 11 shows the time logarithm method based on Sully to evaluate the consolidation coefficient of soil-bentonite wall, taking the data at depths of 3.6 m and 7.1 m as examples [16]. At the depth of 3.6 m, the denominator is the maximum excess pore water pressure of 8.183 kPa, and the molecule is the real-time excess pore water pressure. The time corresponding to U = 0.5 in the figure is t_{50}, t_{50} = 601 s. Similarly, at a depth of 7.1 m, the denominator is the maximum excess pore water pressure of 16.371 kPa and the molecule is the real-time excess pore water pressure. The time corresponding to U = 0.5 in the figure is t_{50}, t_{50} = 1915 s, and then the consolidation coefficient of the soil-bentonite wall is evaluated by the method of standard dissipation type.



(a) At the depth of 3.6 m



(b) At the depth of 7.1 m

Figure 11 is based on Sully's time logarithm method

Figure 12 shows the relationship between consolidation coefficient c_h and t_{50} of non-standard dissipation type based on CPTU. The relationship diagram is based on the results of three different methods: modified t_{50m} method, time square root method and time logarithm method. Among them, the modified t_{50m} method is to modify the t_{50}, and the time square root method is to linearly deduce the measured data to obtain the initial excess pore water pressure. The time logarithm method divides the real-time measured pore pressure by the maximum pore pressure to obtain the normalized pore pressure U. It can be seen from the graph that the time square root method is close to the time logarithm method, and the consolidation coefficient evaluated by the modified c_h method is relatively large.

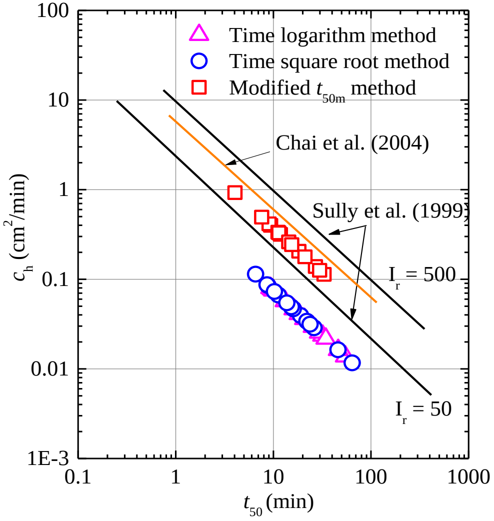


Figure 12 Relationship between c_h and t_{50} of non-standard dissipation types based on CPTU

4 Discussion

In the measured dissipation curve, when the probe penetrates into the soil, the excess pore pressure will appear, then increase to maximum, and finally decrease to the hydrostatic pressure due to the dissipation of excess pore pressure. Therefore, the measured dissipation curve is non-monotonic. Due to different soil layers and different dissipation locations, the t_{50} lines must present different changing shapes.

5 Conclusions

In this paper, the evaluation of consolidation coefficient of soil-bentonite wall based on CPTU is given. Different evaluation methods are used to estimate the consolidation coefficient of soil-bentonite wall according to the type of non-standard pore pressure dissipation. The conclusions are as follows:

(1) For non-standard dissipation types of pore pressure, modified t_{50m} method, time square root method and time logarithm method are used to evaluate the consolidation and permeability characteristics of soil-bentonite wall. The results show that the consolidation coefficient evaluated by the time square root method is close to that by the time logarithm method, while the result evaluated by the modified t_{50m} method is relatively large.

(2) For the case that the dissipation time of non-standard dissipation type is less than t_{50}, the time square root method proposed by Sully can be used to predict the time t_{50} value of half of the excess pore pressure dissipation, so as to evaluate the consolidation and permeability coefficient of soil-bentonite wall. This method shortens the CPTU test period and saves the CPTU test cost.

(3) In the evaluation of consolidation coefficient of non-standard dissipation type of pore pressure, the time logarithm method is actually a simplification of pore pressure dissipation curve, that is, the data during the rise of pore pressure are removed, and the consolidation coefficient is evaluated by time logarithm coordinate with the maximum pore pressure as the initial value. At the depth of 3.6 m and 7.1 m of the soil-bentonite wall, the t_{50} values were 601 s and 1915 s, respectively.

Acknowledgement

The authors are grateful for the financial and technical support provided by the National Key R&D Program of China (2016YFC0800200), the National Natural Science Foundation of China (41672294 and 41877231), Project of Jiangsu Provincial Transportation Engineering Construction Bureau (CX-2019GC02), Colleges and Universities in Jiangsu Province Plans to Graduate Research and Innovation (Grant No. KYCX19-0098) and Scientific Research Foundation of Graduate School of Southeast University (Grant No. YBPY1926).

Reference

[1] Chen, Y. M., Lan, J. W., Li, Y. C., Zhan, L. T., & Ke, H. (2014). Development and control of leachate mound in MSW landfills. Chinese Journal of Rock Mechanics and Engineering, 33(1), pp. 154-163, 2014.

[2] Zhan, L., Guan, R., Chen, Y., & Liu, Z. Monitoring and back analyses of slope failure process at a landfill [J]. Chinese Journal of Rock Mechanics and Engineering, 29(8), pp. 1697-1705, 2010.

[3] D'appolonia D J. Soil-bentonite slurry trench cutoffs. Journal of Geotechnical and Geoenvironmental Engineering, 106(4), pp. 399-417, 1980.

[4] Evans, J. C. Geotechnics of hazardous waste control systems. In Foundation engineering handbook. Springer, Boston, MA, pp. 750-777, 1991

[5] Baxter D Y. Mechanical behavior of soil-bentonite cutoff walls. 2000.

[6] Cai G J, Tong L Y, Liu S Y, et al. Determination of consolidation coefficient for expressway on soft ground from the piezocone penetration test. Journal of Highway and Transportation Research and Development, 190, pp. 131-149, 2007

[7] Torstensson B A. Pore pressure sounding instruments. In:Proceeding of the ASCE Specialty Conference on In Situ Measurement of Soil Properties, American Society of Engineers, Raleigh, North Carolina: 1975.

[8] Chai J C, Carter J P,Miura N, et al. Coefficient of consolidation from piezocone dissipation tests. In:International Symposium on Lowland Technology. pp. 1-6, 2004.

[9] [Sully J P, Robertson P K,Campanella R G, et al. An approach to evaluation of field CPTU dissipation data in overconsol... Canadian Geotechnical Journal. 36(2), pp. 369-381, 1999.

[10] Liu, X., Cai, G., Liu, L., Liu, S., & Puppala, A. J. Thermo-hydro-mechanical properties of bentonite-sand-graphite-polypropylene fiber mixtures as buffer materials for a high-level radioactive waste repository. International Journal of Heat and Mass Transfer, 141, pp. 981-994, 2019.

[11] Liu, L., Cai, G., Liu, X., Liu, S., & Puppala, A. J. Evaluation of thermal-mechanical properties of quartz sand-bentonite-carbon fiber mixtures as the borehole backfilling material in ground source heat pump. Energy and Buildings, 202, 109407, 2019,

[12] House, A. R., Oliveira, J. R. M. S., & Randolph, M. F. (2001). Evaluating the coefficient of consolidation using penetration tests. International Journal of Physical Modelling in Geotechnics, 1(3), pp. 17-26, 2001.

[13] Scott, R. F. New method of consolidation-coefficient evaluation. Journal of the Soil Mechanics and Foundations Division, 87(1), pp. 29-41, 1961.

[14] Robertson, P. K., Sully, J. P., Woeller, D. J., Lunne, T., Powell, J. J. M., & Gillespie, D. G. Estimating coefficient of consolidation from piezocone tests. Canadian Geotechnical Journal, 29(4), pp. 539-550, 1992.

[15] Leung, C. F., Wong, J. C., Manivanann, R., & Tan, S. A. Experimental evaluation of consolidation behavior of stiff clay lumps in reclamation fill. Geotechnical Testing Journal, 24(2), pp. 145-156, 2001.

[16] Li X. Evaluation of impermeability and physical-mechanical characteristics of soil-bentonite cutoff wall based on CPTU. PhD Thesis, Southeast University, 2019.