

MODIFIED ROWE CELL EQUIPPED WITH VANE SHEAR DEVICE OF SOFT COHESIVE SOIL

Ali Kamil Mohsin¹, Lim Jee Wen¹, Ahmad Safuan A Rashid², Suksun Horpibulsuk^{3,*}, Rini Asnida Abdullah⁴, Fauzan Sahdi⁵ and Hossein Moayed⁶

Received: August 14, 2020; Revised: February 02, 2021; Accepted: February 03, 2021

Abstract

The correlation between undrained shear strength, s_u , and overconsolidation ratio, OCR of soft clay is vital for geotechnical analysis and design especially for preloading technique on land reclamation and slurry pond. The oedometer and triaxial or vane shear tests, which are commonly used to determine this relationship are time-consuming. A modified Rowe cell equipped with a vane shear blade was developed to overcome this constrain. The vane shear blade was mounted at the middle of the base of modified Rowe cell and inside the soil sample. The s_u value was measured using the vane blade preinstalled in the soil sample during the consolidation. The relationship between s_u and OCR of a studied kaolin was developed based on the results obtained from the modified Rowe cell. The relationship was represented by a power function similar to the previous studies on clayey soils, indicating the validity of test results from the modified Rowe cell. The modified Rowe cell is a rational and user-friendly alternative device for both research and practical design, which can overcome the problem of time-consuming test procedure and sample disturbance due to the insertion of vane shear blade.

Keywords: Undrained shear strength, overconsolidation ratio, Rowe cell, vane shear, soft clay

Introduction

The overconsolidation ratio, OCR, is a stress state parameter, governing compressibility and undrained shear strength, s_u , of soil (Skempton, 1944; Horpibulsuk *et al.*, 2007; Shen *et al.*, 2014; Bo *et al.*, 2015; Wu *et al.*, 2015). Ladd and Foott (1974) introduced

the useful Stress History and Normalized Soil Engineering Properties (SHANSEP) method to generalize a relationship between s_u and OCR. The s_u versus OCR relationship is essential for geotechnical design (Effendi, 2007; Begaj Qerimi

¹ Department of Geotechnics and Transportation, School of Civil Engineering, Universiti Teknologi Malaysia, Johor, Malaysia.

² School of Civil Engineering, Universiti Teknologi Malaysia and Centre of Tropical Geoengineering (GEOTROPIK), Universiti Teknologi Malaysia, Johor, Malaysia.

³ School of Civil Engineering, Director of Center of Excellence in Innovation for Sustainable Infrastructure Development, Suranaree University of Technology, Nakhon Ratchasima, 30000, Thailand. Tel. 0-4422-4322; Fax. 0-4422-4607; Associate Fellow, Academy of Science, The Royal Society of Thailand, Bangkok 10300, Thailand; E-mail: suksun@g.sut.ac.th

⁴ School of Civil Engineering, Universiti Teknologi Malaysia, Johor, Malaysia.

⁵ Faculty of Civil Engineering, Universiti Malaysia Sarawak, Malaysia.

⁶ Department of Civil Engineering, Kermanshah University of Technology, Kermanshah, Iran.

* Corresponding author

and Mc Namara, 2010; Rashid, 2011). Several research works have established a relationship between s_u and OCR of clay based on both field and laboratory investigations (Almeida and Parry, 1988; Springman, 1989; Sheahan *et al.*, 1996; Springman, 2004).

Jamiolkowski *et al.* (1985) conducted field vane undrained strength and oedometer tests on soft clays to establish a relationship between s_u and OCR . Also, Almeida and Parry (1988) obtained the s_u value using minute vane and cone penetration tests on consolidated kaolin and Gault clay. Since both vane and penetrometer must be inserted into the consolidated soil prior shearing, the insertion can cause the sample disturbance and affect the measured shear strength. Springman (1989) conducted a series of vane shear tests in a centrifuge on kaolin and proposed a relationship between s_u and OCR . However, this test was very costly. Phillips and Valsankar (1987) investigated the effect of grain size on penetration resistance of penetrometer. They found that the effect of grain size was insignificant if the ratio of the probe diameter to sand grain size was bigger than 20.

A series of triaxial tests was conducted by Sheahan *et al.* (1996) to investigate the effect of strain rate on undrained shear strength, s_u under different OCR values of Boston Blue Clay (BBC) sample. The consolidation of samples was done using an incremental consolidation loading device (Rowe cell) to apply different OCR values (Davidson, 1980; Almeida and Parry, 1988; Begaj Qerimi and Mc Namara, 2010). The samples were trimmed, covered with a cellophane and kept in a damp room before the triaxial test. The triaxial tests were conducted under different strain rates (0.05%, 0.5%, 5%, and 50%/h) and OCR values. Sheahan *et al.* (1996) found that the s_u of BBC depends on the stress history and strain rate. The procedure proposed by Sheahan *et al.* (1996) needs a care to transfer the consolidated samples from the consolidation device to the triaxial cell. Moreover, the K_0 -consolidation in triaxial test is complicated and time-consuming. To overcome the sample disturbance, complex test procedure and time constraints, a fully equipped device must be developed to measure the accurate undrained shear strength at various vertical effective stress and stress history values.

This research therefore attempts to develop a modified Rowe cell with vane shear device to prepare and consolidate the soil samples and measure the corresponding s_u . Kaolin was used as a studied soil, which is typical non-swelling clay, normally found in various countries (Horpibulsuk *et al.*, 2007). A series of tests was carried out by consolidating kaolin samples under different OCR

values, of which the maximum value was 10. From the analysis of test results, the relationship between s_u and OCR of kaolin clay was developed and compared with those from previous studies to validate the applicability of the modified Rowe cell.

Rowe Cell Equipped with Vane Shear Blade

The modified Rowe cell with vane shear apparatus was developed to investigate the influence of vertical effective stress and stress history on remolded clay as shown in Figure 1. Drainage occurs vertically downwards and upwards and pore water pressure is measured at the center of the base. Two instruments; a pore pressure transducer and a Linear Variable Displacement Transducer (LVDT), were equipped in the modified Rowe cell test for data acquisition. A 50 mm LVDT having an accuracy of 0.001 mm was utilised to measure the vertical displacement of the soil sample during the consolidation test. A 1,500 kPa pore pressure transducer with accuracy of 0.1 kPa was used to measure the diaphragm pressure and pore pressure at the bottom of the Rowe cell. All the data were acquired using Winhost 5 logging software for Windows and kept in a personal computer.

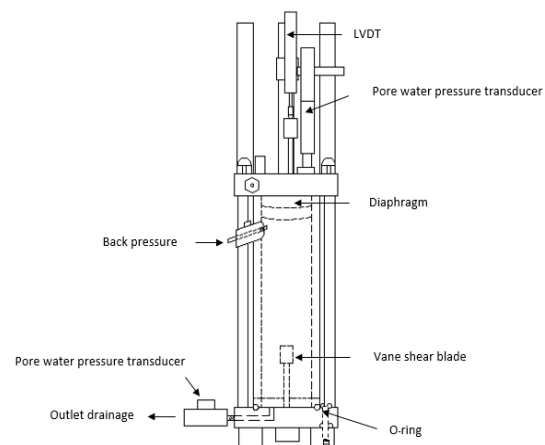


Figure 1. Schematic diagram of a modified Rowe cell

A modification on the Rowe cell base was made by mounting the vane blade in the middle of the base as shown in Figure 2. An O ring was utilised to cover the gap in-between the Rowe cell base and the vane rod to prevent leakage throughout the consolidation and shear tests. The vane rod was projected out of the Rowe cell base to be joined with the vane shear apparatus to subject and quantify the torque force on the soil sample. After completion of consolidation, the cell was rotated as shown in Figure 3 and the extension of the vane shear blade was attached to the manually operated vane shear

apparatus (EL26-2270) for the torque force to be applied. The torque was generated via the 12.7×12.7 mm vane by spring using a shearing rate of 10° per min. Assuming the soil deforms as a cylinder whilst the vane blade rotates and the shear stress distribution at the top and bottom faces of this cylindrical failure mechanism is uniform, the s_u at the termination of the experiment is calculated using Equation 1 (Powrie, 2002);

$$s_u = \frac{\tau}{\pi \left[\frac{d^2 h}{2} + \frac{d^3}{6} \right]} \quad (1)$$

where τ is the torque applied and H and D are vane blade's height and diameter, respectively.

The angular deflection reading indicated by the pointer on the inner scale after each shear test gave the relative angular deflection Θ_f (degrees) of the ends of the springs at failure. The applied torque, τ (N.mm), is equivalent to $C_s \times \Theta_f$, where C_s is the calibration factor (N.mm/degree). Figure 4 shows the results of spring calibration with the coefficient of determination $R^2 = 1$. The friction between the base of the Rowe cell and the rod was measured by applying a rotating force on the vane blade (without the soil sample). The value of friction between the

rod of the vane shear and the wall base was obtained to be 1.96 kPa.

Materials and Methods

In this study, the kaolin powder sample was supplied by Kaolin Malaysia Bhd. It contains more than 80% clay particles (size under 0.425 μm) and has a specific gravity G_s of 2.65. The basic soil properties are shown in Table 1. The Liquid Limit (LL) and Plastic Limit (PL) were 54.0% and 29.1%, respectively. Thus, the Plasticity Index, PI, was 24.9%. Based on the Unified Soil Classification System, the kaolin was classified as high plasticity clay (CH) and has the group name of sandy fat clay.

1 kg of dried kaolin was mixed with deaired water using a food mixer for approximately 10 min to provide a homogeneous mixture at a water content of 108% (2 LL) as suggested by Sheeran and Krizek (1971); Raftari *et al.* (2014); Rashid *et al.* (2015a, 2015b, 2018) and Bunawan *et al.* (2018). To avoid insertion effect of the vane shear blade, the blade was mounted on the Rowe cell base. The base and cell were assembled and Vyon F porous plastic was laid on the bottom of the Rowe cell. The slurry was then carefully poured inside the cell to a desired height and the soil surface was covered by the Vyon F porous plastic. The top Rowe cell and diaphragm were mounted carefully on the top of the porous plastic. The cell was sealed using the bolt between the Rowe cell top and base. All the preparation for the Rowe cell followed the procedure outlined in Britis Standard 1377 (1990).

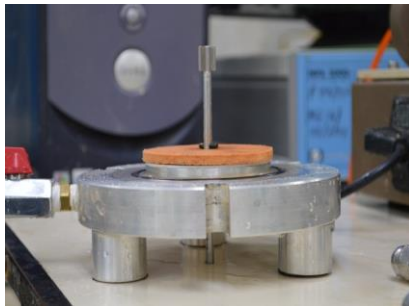


Figure 2. Photograph of modified Rowe cell base and vane shear blade

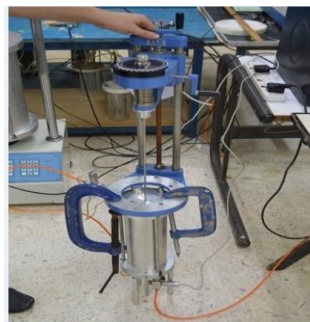


Figure 3. Determination of s_u using vane shear apparatus

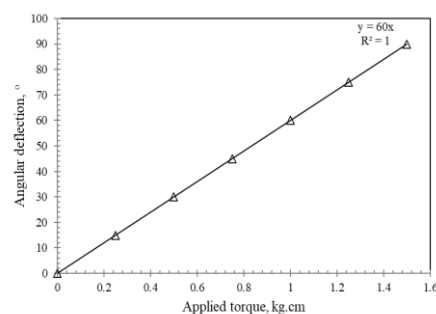


Figure 4. Spring calibration results

Table 1. Soil classification of kaolin clay

Soil properties	Value
Liquid Limit, LI	54.0
Plastic Limit, PL	29.1
Plastic Index, PI	24.9
Soil type	CH
Specific gravity, G_s	2.65

A small pressure of approximately 3.13 kPa was first applied on the sample to avoid squeezing of soil sample out from the cell during the consolidation process (Rashid, 2011). After 48 h, a second layer of slurry was poured and 3.13 kPa of pressure was re-applied. This process was conducted to obtain a desired sample height. The magnitude of the next applied vertical stress was 6.25 kPa, and was followed by 12.5, 25, and finally 50 kPa as the maximum stress. Starting at 3.13 kPa, the LVDT was mounted on the spindle fully extended, so that it touched the center of the consolidation piston. It was used to record the vertical displacements with the changes of the consolidation stress. Each step of stress increment was applied after consolidation had been completed under the previous applied stress (British Standard 1377, 1990). After completion of consolidation under a stress of 50 kPa, the stress was reduced in three steps to 25, 10, and then 5 kPa to produce an overconsolidated sample for each test with respective OCR values of 2, 5, and 10. In addition, the normally consolidated clay (OCR = 1) was prepared by maintaining the stress at 50 kPa. It was noted that the pore pressures reached a stable and almost zero value when the consolidation exceeds 24 h for each stage. Approximately nine days were spent to complete the series of consolidation stresses.

Results and Discussion

Modified Rowe Cell Test Results

Consolidation Characteristics

The consolidation curves of the four kaolin samples are shown in Figure 5. The values of the compression index, C_c , and swelling index, C_s , respectively ranged from 0.33 to 0.36 and 0.004 to 0.010. The standard deviations of C_c and C_s were found to be less than 0.04 and 0.005, respectively. In addition, the results of C_c and C_s were within those suggested by Skempton (1944) for remolded clay.

The logarithmic curve of the coefficient of consolidation versus consolidation stress plot is shown in Figure 6. The coefficient of consolidation reduces proportionally with increasing the consolidation stress, which agrees with the theory of consolidation (Holtz and Kovacs, 1981).

Undrained Shear Strength

The s_u of the kaolin was determined at the completion of the consolidation test by using vane shear and the s_u was determined using Equation 1. Table 2 summarizes the values of angular deflection and undrained shear strength under different values

of OCR. Based on the results, a relationship between

the normalized $\frac{s_u}{\sigma'_v}$ and OCR was proposed and

is shown in Figure 7 where $\left(\frac{s_u}{\sigma'_v}\right)_{n.c}$ is referred to the

s_u to σ'_v ratio at OCR = 1. Figure 8 showed that the normalized strengths measured by the modified Rowe cell, compared to the results of (Almeida and Parry, 1988) obtained by vane shear testing and those of Davidson (1980) obtained by triaxial testing. Both figures show the same trend of the relationships obtained from this study and the previous studies. However, the measured s_u values in the present study are slightly higher than those reported the previous studies, possibly due to the different types of clay and the less sample disturbance in shearing process of the developed device. The similar relationship between the s_u and OCR from the study and the previous studies shows the applicability of the developed device as a rational and practical alternative to the conventional oedometer and triaxial or vane shear apparatuses.

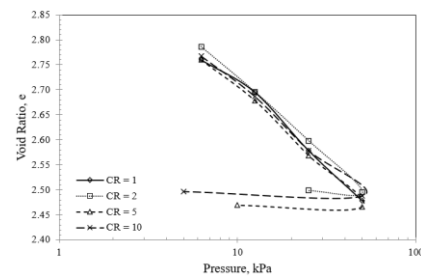


Figure 5. Consolidation characteristic of kaolin clay

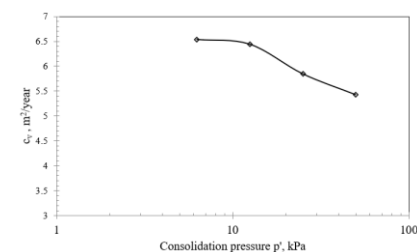


Figure 6. Coefficient of rate of consolidation versus consolidation pressure

Table 2. Results of consolidation ratio and undrained shear strength of kaolin clay

Consolidation ratio, OCR	Angular deflection, Θ_t	Undrained shear strength, s_u (kPa)
1	22.3	8.5
2	21.8	8.3
5	20.4	7.8
10	18.0	6.9

Based on the results presented in Figures 7 and 8, Equation 2 was developed for the studied kaolin and is expressed as:

$$\frac{s_u}{\sigma'_v} = 0.16(OCR)^{0.9} \quad (2)$$

where σ'_v is the vertical effective stress and the power in Equation 2 is the gradient of the relation in Figure 7 and the normalized undrained strength of the normally consolidated reconstituted clay was obtained from the y-axis intercept in Figure 8. Excess pore water pressure during the vane shear test at the bottom base of the cell was recorded and

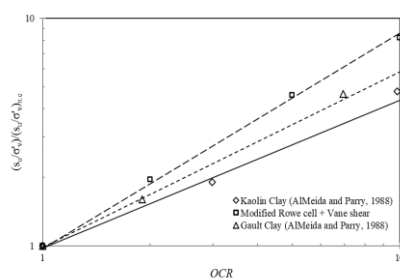


Figure 7. Normalized $\frac{s_u}{\sigma'_v} \left(\frac{s_u}{\sigma'_v} \right)_{n.c.}$ and OCR for kaolin and Gault clay

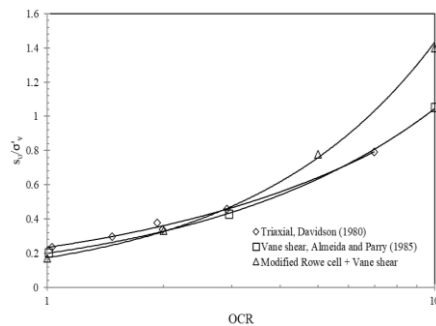


Figure 8. Normalized s_u with OCR for kaolin clay

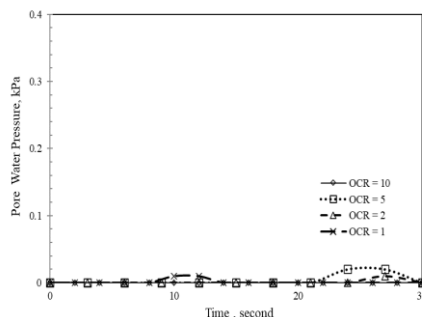


Figure 9. Pore water pressure results during vane shear test

is presented in Figure 9. The measured excess pore water pressures were almost zero for all OCR values tested. This indicated that the soil samples were large enough to minimize the boundary effect; hence, the proposed s_u and OCR relationship was reliable.

Available undrained shear data from Effendi, (2007); Rashid (2011); Nasroulla *et al.* (2016) were collated to examine the reliability of Equation 2. A special fabricated testing chamber was invented by Effendi (2007); Rashid (2011); Nasroulla *et al.* (2016) to prepare and consolidate the kaolin samples to have OCR values of 2 and 10 (NaEffendi, 2007; Rashid, 2011; Nasroulla *et al.*, 2016). The consolidated samples were taken from the chamber and determined s_u using a hand vane shear device. The measured s_u at various σ'_v and OCR values are listed in Table 3. The predicted s_u values were 14% to 20% higher than the measured values at the same OCR and effective vertical stress values due to the difference in soil sample and hand vane device. This confirms that the developed equation could predict the s_u value under OCR less than 10 and can overcome the effect of sample disturbance during sample preparation and insertion of vane shear blade.

Table 3. The results of s_u , σ'_v and OCR values obtained by Effendi (2007); Rashid (2011) and Nasroulla *et al.*, (2016)

Researcher	σ'_v (kPa)	OCR	s_u (kPa)	Average s_u (kPa)	s_u (kPa) (Eq. 2)
Nasroulla <i>et al.</i> (2016)	25.0	2.0	7.2	6.4	7.5
	25.0	2.0	6.6		
	25.0	2.0	7.2		
	25.0	2.0	5.6		
	25.0	2.0	6.6		
	25.0	2.0	6.6		
Rashid (2011)	5.0	10.0	5.7	5.7	6.4
	5.0	10.0	5.6		
	5.0	10.0	5.7		
Effendi (2007)	5.0	10.0	5.3	5.1	6.4
	5.0	10.0	4.8		
	5.0	10.0	5.3		
	5.0	10.0	4.8		

Conclusions

In the present research, the modified Rowe cell device was developed and capable to investigate the influence of vertical effective stress and stress history on the s_u of the remolded clay, which is vital for geotechnical design especially for land reclamation and slurry pond improvement. The device can address the time-consuming problem from the conventional consolidation and shear tests.

The test results on studied kaolin was used to validate the applicability of the developed device. The relationship between s_u and OCR was formulated in power function, which is comparable to the previous studies. The measured s_u values obtained from the developed device were found to be higher than those from the conventional vane shear device showing that the developed equation can eliminate the sample disturbance from sample preparation and insertion of vane blade.

Acknowledgements

The authors are pleased to acknowledge the Ministry of Education of Malaysia for the Prototype Research Grant Scheme (R.J130000.7822.4L620) and Universiti Teknologi Malaysia for providing the research funds (Q.J130000.2451.09G23).

References

- Almeida, M.S.S. and Parry, R.H.G. (1988). Miniature vane and cone penetration tests during centrifuge flight. Vane shear strength testing in Soils: Field and Laboratory Studies. In: Richards, A.F. (ed.) ASTM STP 1014. American Society for Testing and Materials. Philadelphia, p. 209-219.
- Begaj Qerimi, L. and Mc Namara, A.M. (2010). Physical modelling for pile foundation re-use. Proceedings of the 7th International Conference on Physical Modelling in Geotechnics (ICPMG 2010), Zurich, Switzerland. Taylor and Francis Group: London, 2:733-738.
- Bo, M.W., Arulrajah, A., Sukmak, P., and Horpibulsuk, S. (2015). Mineralogy and geotechnical properties of Singapore marine clay at Changi. *Soils Found.*, 55(3):600-613.
- British Standard 1377. (1990). British Standard Method of the Test for Soils for Civil Engineering Purposes: Part 6, Consolidation and Permeability Tests In Hydraulic Cells And With Pore Pressure Measurements. British Standard Institution [BS], London.
- Bunawan, A.R., Momeni, E., Armaghani, D.J., Nissa M.S.K., Rashid, A.S.A. (2018). Experimental and intelligent techniques to estimate bearing capacity of cohesive soft soils reinforced with soil-cement columns. *Measurement: J. Int. Measure. Confed.*, 124:529-538.
- Davidson, C.S. (1980). The shear modulus of clay. Part II Research Report. Cambridge, England: Cambridge University Engineering Department, United Kingdom.
- Effendi, R. (2007). Modeling of the settlement interaction of neighboring buildings on soft ground, [PhD thesis]. University of Sheffield, United Kingdom.
- Holtz, R.D. and Kovacs, W.D. (1981). An Introduction to Geotechnical Engineering. Prentice Hall, New Jersey.
- Horpibulsuk, S., Shibuya, S., Fuenkajorn, K., and Katkan, W. (2007). Assessment of engineering properties of Bangkok clay. *Canadian Geotech. J.*, 44(2):173-187.
- Jamiolkowski, M., Ladd, C.C., Germaine, J.T., and Lancellotta, R. (1985). New developments in field and laboratory testing of soils. Proceedings of the 11th International Conference on Soil Mechanics and Foundations Engineering. San Francisco, 1:57-153.
- Ladd, C.C. and Foott, R. (1974). New design procedure for stability of soft clays. *J. Geotech. Geoenviron. Eng.*, 100(GT7):763-786.
- Nasroulla, N.A., Rashid, A.S.A., Kalatehjari, R., Noor, N.M., Kassim, K.A., and Horpibulsuk, S. (2016). Determination of liquid limit of a low swelling clay using different cone angles. *Appl. Clay Sci.*, 132(133):748-752.
- Phillips, R. and Valsangkar, A. (1987). An experimental investigation of factors affecting penetration resistance in granular soils in centrifuge modelling. Technical Report CUED/DSOILS/TR210. Cambridge University Engineering Department, United Kingdom.
- Powrie, W. (2002). Soil mechanics: concepts and applications. London and New York: Spon Press, Taylor and Francis Group, New York.
- Raftari, M., Rashid, A.S.A., Kassim, K.A., and Moayedi, H. (2014). Evaluation of kaolin slurry properties treated with cement. *Measurement*, 50:222-228.
- Rashid, A.S.A. (2011). Behaviour of weak soil reinforced with soil columns formed by the deep mixing method, [PhD thesis]. University of Sheffield, United Kingdom.
- Rashid, A.S.A., Black, J.A., Mohamad, H., and Mohd Noor, N. (2015a). Behavior of weak soils reinforced with end-bearing soil-cement columns formed by the deep mixing method. *Marine Geores. Geotech.*, 33(6):473-486.
- Rashid, A.S.A., Black, J.A., Kueh, A.B.H., and Md Noor, N. (2015b). Behaviour of weak soils reinforced with soil cement columns formed by the deep mixing method: Rigid and flexible footings. *Measurement: J. Int. Measure. Confed.*, 68:262-279.
- Rashid, A.S.A., Kueh, A.B.H., Mohamad, H. (2018). Behaviour of soft soil improved by floating soil-cement columns. *Int. J. Phys. Model. Geotech.*, 18(2):95-116.
- Sheeran, D.E. and Krizek, R.J. (1971). Preparation of homogeneous samples by slurry consolidation. *J. Mater.*, 6(2):356-373.
- Sheahan, T.C., Ladd, C.C., and Germaine, J.T. (1996). Rate-dependent undrained shear behavior of saturated clay. *J. Geotech. Eng.*, 122(2):99-108.
- Shen, S.L., Wu, H.N., Cui, Y.J., and Yin, Z.Y. (2014). Long-term settlement behavior of the metro tunnel in Shanghai. *Tunnel. Underg. Space Technol.*, 40:309-323.
- Skempton, A.W. (1944). Notes on the compressibility of clays. *Quarterly J. Geol. Soc. London*, 100(1-4):119-135.
- Springman, S. (2004). Modeling in geotechnics: Course notes. ETH Zurich, Institute of Geotechnical Engineering.
- Springman, S.M. (1989). Lateral loading on piles due to simulated embankment construction, [PhD dissertation]. University of Cambridge, United Kingdom.
- Wu, H.N., Shen, S.L., Ma, L., Yin, Z.Y., and Horpibulsuk, S. (2015). Evaluation of the strength increase of marine clay under staged embankment loading: a case study. *Marine Geores. Geotech.*, 33(6):532-541.