Determination of apparent earth pressure for stiff wall systems in soft clays

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ABSTRACT

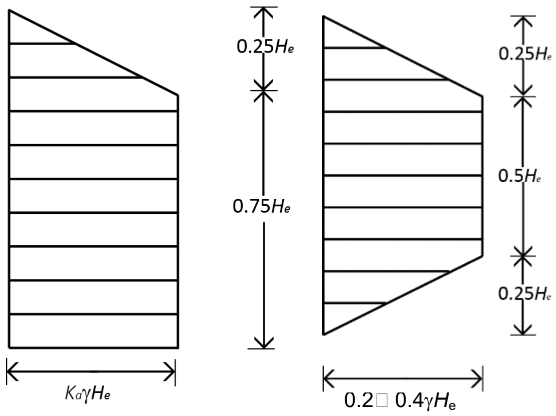
The apparent pressure diagrams (APD) and the distributed prop loads (DPL) proposed by previous studies are basically developed with limited field measurements involving relatively flexible walls. In recent years, rigid diaphragm walls appeared in large numbers substantiate the need to further investigate the applicability of the APD. This study firstly proposes the updated APD for stiff wall systems in soft clay based on extensive field instrumentations from case histories, parametric studies are subsequently carried out by PLAXIS to investigate the effects of clay thickness, wall stiffness and soil-wall interface characteristics on the earth pressure. The updated apparent pressure diagram and the parametric analysis results are to provide a reasonable basis for design and check.

Keywords: apparent earth pressure, braced excavation, clay, strut forces, stiff walls;

1 INTRODUCTION

The past 20 years have witnessed the most rapid development of excavations in the world, at present, with the booming of various high-rise buildings as well as underground engineering, higher requirements are put forward for the increasingly deep excavations, of which an inadequate strutting can result in progressive failure and even total collapse. Based on strut load envelopes from a number of subway subjects, Terzaghi and Peck (1967) developed an empirical method to estimate the strut load for various general types of soil in multi-braced excavations, the apparent pressure diagram (APD) of clay proposed by them was shown in Fig. 1, the design strut loads of braced excavations could be calculated using a tributary method applied onto the relevant APDs. Further, Chang and Wong (1996) found that the Terzaghi and Peck (1967)'s APD for clay was unconservative and proposed a modified APD for diaphragm walls in deep clay deposits, later, the further case histories collected by Twine and Roscoe (1999) also suggested that Peck's tentative recommendations for excavations involving stiff walls are not conservative. Currently, several researchers (Cham and Goh 2011, Goh et al. 2017) have focused on the performance for the stiffer wall from either numerical analysis or limited field measurements and have drawn some useful conclusions.

This study firstly proposes the updated APD for multi-propped excavation involving stiff wall systems in soft clay based on extensive field instrumentations from case histories worldwide. The effects on the maximum earth pressure from factors such as clay thickness, wall stiffness and soil-wall interface characteristics are also investigated via parametric analysis using PLAXIS 2D, relationship between each parameters and maximum strut force was identified and presented.



(a) Soft to medium clays (b) Stiff Clay
Fig.1. APD for design of struts (adapted from Peck 1969)

2 APPARENT EARTH PRESSURE ENVELOPE FOR STIFF WALLS

For the case of excavations with stiff walls, the proposed distributed prop loads (DPL) by Twine and Roscoe (1999) were based on very limited field data, with more recent field instrumentations from case histories involved in the published literatures listed in Table 1, updated APD was proposed and compared with Peck's APD and CIRIA DPL recommendations (Twine & Roscoe 1999).

The normalized apparent earth pressure for this case is shown in Fig. 2, based on the measured strut forces from the case histories domestic and overseas, for normalized depth z/He≤0.25, the normalized apparent earth pressures of the data are less than 0.5, and Peck's APD usually underestimates the earth pressure, while for z/He>0.25, the normalized apparent earth pressure is generally less than 1.0, with a number of the measured data beyond the limit value proposed by previous studies.

Table 1 Summary of case histories in soft clay with stiff walls

Case histories	Unit weight (kN/m3)	He(m)	No. of Strut levels	Horizontal strut spacing(m)	Vertical strut spacing(m)	References
BTG residual soils	18.5-19.2	19.5-24.0	4-6	4.2-8.5	4.0-6.0	Goh et al. (2017)
Taipei (CIRIA report) AS1	17.5	14.4	4	5.5	4.0,3.8,2.9,2.3	Twine and Roscoe (1999)
Taipei (CIRIA report) AS2	19.2	14.1	4	6.0	2.7,2.9,3.4,3.4	Twine and Roscoe (1999)
Singapore Circle Line projects	16.0	18.0	4	–	–	Cham and Goh (2011)
Singapore Old Alluvium soil sites	–	–	–	–	–	Li (2001)
Shanghai CBD deep excavation	17.2	17.5	4	–	4.4,4.6,4.0,4.6	Lau et al. (2010)
Singapore C907 site, CST 3A	18.0	16.0	5	5	1.0,3.0,3.0,3.0,3.0	Jadhav (2011)
Singapore C907 site	18.0	15.0	4	6	2.5,3.0,3.5,4.0	Jadhav (2011)
Wuxi, China	20.5	16.1	4	3	1,3,5,4	Chen (2013)
Hangzhou, China	17.3-19.5	16.8	4	6	3.8,3,3,3	Liu (2015)
Hangzhou, China	17.3-19.3	24.3	6	6	1.9,5.2,3.6,3.3,3.7,3.3	Zhang et al. (2014)
Shanghai, China	17.5	15.8	5	3	1.2,3.6,2.4,2.8,2.8	Ding (2009)
Suzhou, China	19	15.6	3	–	1,6,4.8	Liao et al. (2015)
Qingdao, China	17.5-19.0	19.0	4	5	4.5,3,3,5	Liu (2013)
Nanning, China	19.7	17	3	9,3,3	2,5,4.5	Pan (2011)
Changchun, China	19.7	18.5	3	3	5.5,6,7	Zhou (2011)
Wuhan, China	18	17.6	4	3	3.9,5.1,4.2,4.5	Huo and Liao (2016)

Thus, for the case of excavations in soft clays with stiff walls, an updated APD of 0.5γHe for z/He≤0.25 and 1.0γHe for z/He>0.25 is proposed, as shown in Fig. 2, by the red solid lines.

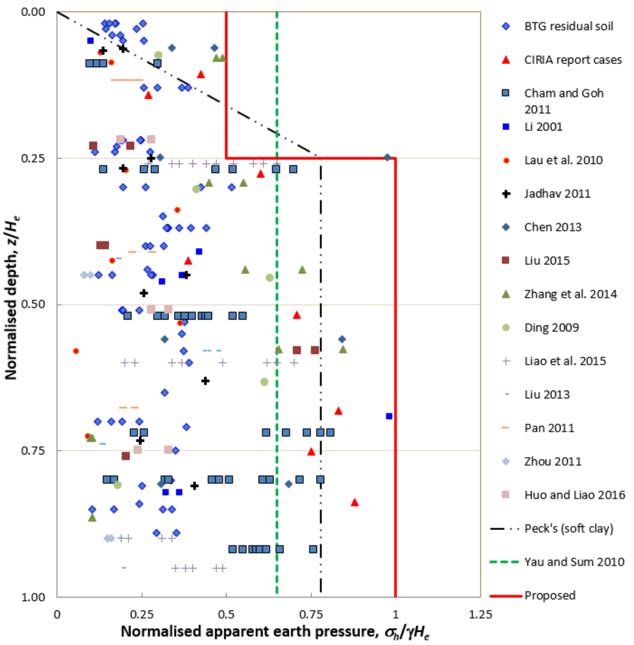


Fig.2. Normalized apparent earth pressure in soft clay

3 PARAMETRIC STUDY

To better understand the change rule of earth pressure during excavation in soft clay, parametric studies were carried out in this section, the effects of clay thickness T, soil-wall interface characteristics β and wall stiffness EI (d) on the normalized apparent earth pressure are studied, the software package Plaxis 2D (2017) with the Hardening-soil with small strain (HSS) model described by Benz (2007) is used in all the numerical analyses.

3.1 Geometry and soil characteristics

Fig. 3 shows the typical geometry of the models, the original water table is assumed to be at ground surface, the water table inside the excavation was progressively lowered as the excavation proceeds. Typical excavation sequence can be seen in zhang et al. 2015.

Hardening-soil with small strain (HSS) model for the soft clay was adopted in the numerical analyses, it is an improvement of the HS model (Schanz et al. 1999), to describe the behavior of soil at small strain which is less than 10^{-3}, two additional parameters, the initial shear modulus G_0^{ref} and the shear strain $\gamma_{0.7}$ are defined in HSS. More details about HSS models and the determination of the parameters adopted in present numerical analyses can be referred in zhang et al. 2015 and Liang and Jia (2017).

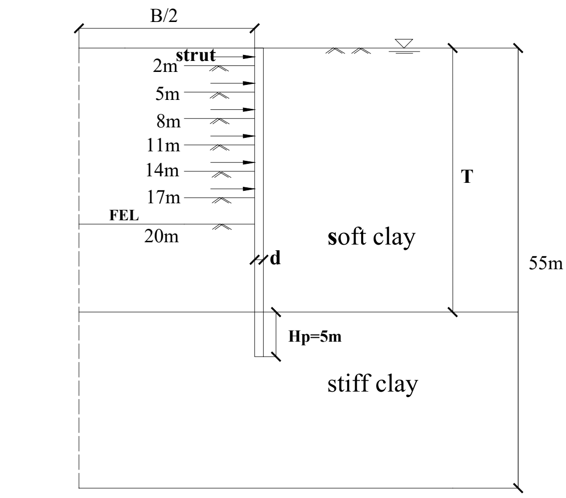


Fig.3. Cross-section of the model in parametric study

As suggested by Xuan (2009), the effect of excavation width B, soil unit weight γ and relative soil stiffness ratio E_{50}/c_u don't affect the earth pressure significantly, in this paper, excavation width B was fixed at 30m, γ of the soft soil are set to be constant at 17kN/m^3, and E_{50}/c_u equals to 200. The MC constitutive relationship was used to model the stiff clay (γ = 20 kN/m^3, c_u = 500 kPa, E_u = 250 MPa) underlying the soft clay deposit. For simplicity, the strut stiffness EA was assumed at 3.80×10^{6}kN/m and the Young's modulus of the retaining wall was kept as constant (E_{wall} = 2.0×10^7 kN/m^2).

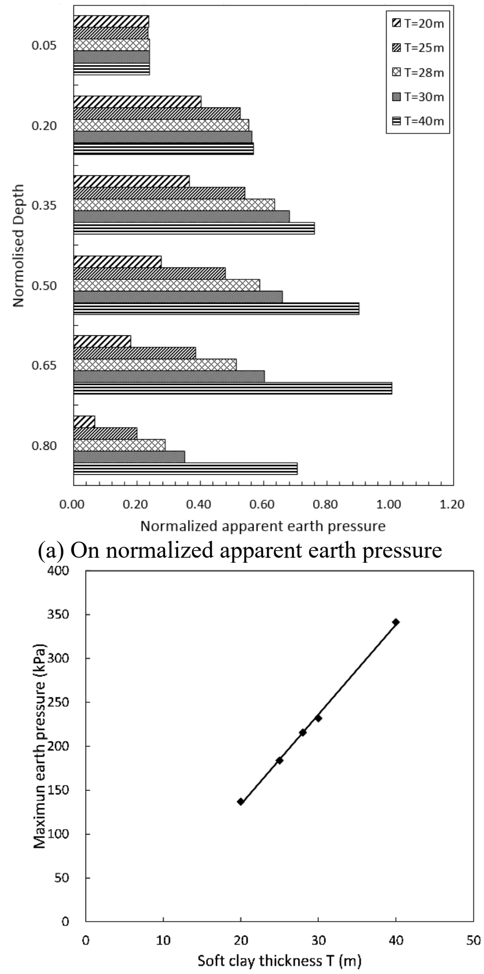
One set of cases extracted from Xuan (2009) are used as the basic model of the parametric study, where excavation depth He=20m, relative shear strength ratio c_u/σ_v'=0.25 (i.e. the effective friction angle φ=22.3° and the reference secant stiffness E_{50}^{ref}=8062kPa), the embedded depth into stiff clay Hp=5m, the input parameters of soft clay was tabulated in Table 2. Other parameters for clay thickness T=20, 25, 28, 30, 40m, soil-wall interface characteristics β=0.6, 0.7, 0.8, 0.9, 1.0, wall stiffness EI=0.36×10^6 (d=0.6m), 1.215×10^6 (d=0.9m), 2.88×10^6 (d=1.2m), 5.625×10^6 (d=1.5m) kNm^2/m were adopted to study the effect of various influential factors on earth pressure.

Table 2 Input soil parameters of the soft clay

Parameters	Unit	Value
γ	kN/m^3	17
E_{50}^{ref}	kN/m^2	8062
E_{ur}^{ref}	kN/m^2	$3E_{50}^{ref}$
c		0.05
φ	°	22.3
ψ	°	0
K_0^{nc}	[-]	0.67
$\gamma_{0.7}$	[-]	2E-4
ν_{ur}	[-]	0.2
G_0	[-]	44120

3.2 Numerical results

Fig.4 shows that soft clay thickness has a significant effect on the magnitude of strut loads, Fig.4 (a) also indicates that the point where maximum pressure occurs gradually move down as the clay thickness increases. The shape of the maximum pressure plotted with different clay thickness shown in Fig.4 (b) indicates the pressure changes almost linearly with the clay thickness.



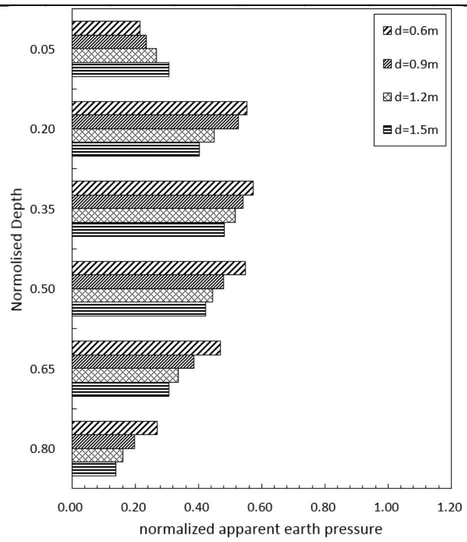
(a) On normalized apparent earth pressure

(b)On maximum earth pressure

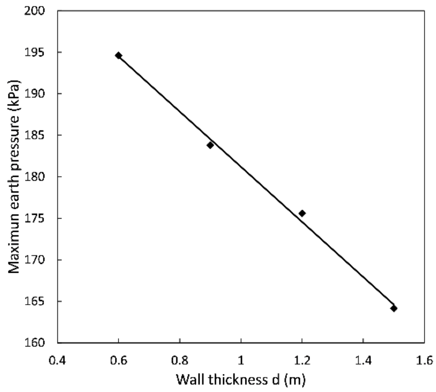
Fig.4. Effect of soft clay thickness on earth pressure

Stiff walls ranging from 0.6m to 1.5m thick, which represent an almost 16 times increasing in wall stiffness. As evidenced in Fig.5, the greater of the wall stiffness, the smaller of the earth pressure, and from Fig.5 (b), it also shows the maximum earth pressure increases almost linear with wall stiffness.

Furthermore, the effect of soil-wall interface characteristics on earth pressure was also discussed, for simplicity, the diagram of the effect of soil-wall interface characteristics on earth pressure was omitted here. It found that when interface strength β ranges from 0.6~1.0, it doesn't significantly change the magnitude of the maximum earth pressure nor the distribution of it. As suggested by Huang et al. 2012, β always equals to 0.65 in clay.



(a) On normalized apparent earth pressure



(b) On maximum earth pressure

Fig.5. Effect of wall stiffness on earth pressure

4 SUMMARY AND CONCLUSION

Based on field measurement, an updated APD was proposed for stiff wall systems in soft clay, parametric study also found that the maximum earth pressure has a significant linear correlation with soft clay thickness and retaining wall stiffness, while soil-wall interface characteristics β has little effect on earth pressure.

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