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Conversion factor analysis of self-balanced loading test of cast-in-situ piles based on analogue test method

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Abstract: Based on the characteristics of pile-soil interaction and the Mohr-Coulomb strength theory, a new method of determining the side friction at a pile-soil interaction is proposed. Combined with the actual engineering cases, the effectiveness of the analogue test method is verified by comparing it with the traditional anchor pile method and self-balanced method. Taking the self-balanced test of the bridge pile foundation in the Songhua River as an example, the conversion factor of sandy soil and weathered mudstone are confirmed by the analogue test method. The results show that the conversion factor of sandy soil and weathered mudstone in the Songhua River area should consider the geological conditions and the construction technology, etc. The standard values are relatively conservative. It is suggested that the engineering application should be properly revised. The recommended range of the conversion factor of sandy soil in this area is 0.65 to 0.85, and that of weathered mudstone is 1.0.

Key words: cast-in-situ piles; self-balanced method; analogue test method; Mohr-Coulomb strength theory; conversion factor

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The traditional static load test is the most effective method to determine the vertical bearing capacity of the pile foundation, but its application is usually restricted by special environment, engineering cost, pile foundation type and so on. To solve this problem, a pile-end loading test method was firstly proposed by Nakayama and Tujiseki[1] in 1969. Osterberg[2] applied the technique in engineering practice, and then introduced it to the public. Gong et al.[3] from Southeast University applied the technique to numerous practical projects and complied several technical regulations about the self-balanced method. At present, the self-balanced method has been widely used in bridge, building and road construction to determine the vertical bearing capacity of various types of pile foundation[4-6]. Thus, a complete theory system and calculation method for the self-balanced loading test has been created in China.

The theory system and calculation method of the self-balanced loading test are different from that of the traditional static loading test. The largest difference is the conversion factor which is used to convert the self-balanced test result into that of the traditional static loading test. Much research has been carried out to determine the appropriate value of the self-balanced test conversion factor. Li et al.[7] analyzed the value of the self-balanced conversion factor in sandy soil and applied it in similar engineering applications. Kim et al.[8-9] studied the side friction in the self-balanced test and traditional static loading test by numerical study and experiments. The results show that the side friction was related to the pile slenderness ratio, soil properties and soil drainage condition. Dai et al.[10] proposed a range of self-balanced conversion factors in different soils by comparing them with the results of the same soil layers through the self-balanced test and traditional static loading test at the same construction sites. The self-balanced test and the traditional static loading test are commonly used to determine the conversion factor value in the existing literature, which is costly and has a large error in test results. Therefore, it is useful to find a more economical and effective method to determine the value of the conversion factor with efficiency and accuracy.

The analogue test method is a new approach to calculating the bearing capacity of the pile foundation. It is based on the similarity principle and considers the influence of factors such as formation environment and construction technology. Based on the Mohr-Coulomb strength theory, the side friction of the pile and tip resistance are analyzed by laboratory tests[11]. Leng et al.[12-14] put forward a method to determine the parameters in the analogue test method, and confirmed their effectiveness by comparing them with the results from a self-balance loading test in a real project. In this paper, combined with the typical bridge engineering cases, a new method for determining the self-balanced conversion factor is pro-

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posed by the analogue test method. Furthermore, the conversion factors of sandy soil and weathered mudstone in the Songhua River area are proposed to provide engineering experience in applications.

1 Test Principle and Method

1.1 Analogue test method

The analogue test (see Fig. 1) uses the medium direct shear apparatus to carry out the side friction test. Through the analysis of the lithology of the test pile location, the pile-soil interaction is simulated by considering the actual geological environment. According to GBJ 123—1999[15], the vertical and horizontal displacements of the direct shear test are measured by the displacement sensor, the vertical load is applied, and the shear rate is controlled in 0.4 mm/min. The pile deformation is regarded as stable if the horizontal displacement does not change with the horizontal shear force. By changing the normal stress of the specimen, the stress-strain curve of the specimen is obtained, then the cohesive strength c and the internal friction angle φ between the pile and soil is also given. Finally, the side friction between the pile and soil is determined by the Mohr-Coulomb principle.

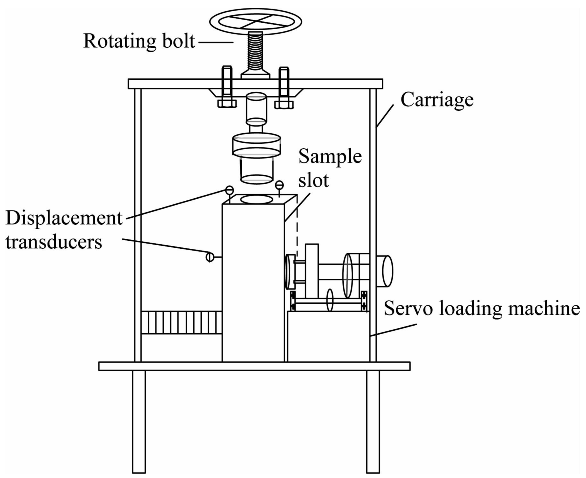

Fig. 1 Schematic diagram of medium direct-shear apparatus

In addition, by the method of smearing the surface of sample, the influence of the pile construction on the interaction between the pile and soil is simulated. Considering the thickness of the shear zone, the relative slippage between the pile and soil is simulated as much as possible. The results show that the shear zone between the pile and soil is very thin, and slippage can be simulated by determining the thickness of the shear zone in a laboratory test[14].

Due to the action of self-weight or additional stress, the effective stress of soil around the pile changes the normal stress on the surface of the pile and soil. The normal stress of the pile surface is related to the characteristics of soil, additional stress and drainage conditions. Considering the properties of different soil layers, the normal stress at different sampling depths is predicted. The normal stress is applied by hierarchical loading, which is divided into five levels: σ_1, σ_2, σ_3, σ_4 and σ_5. The diagram of the normal stress calculation is shown in Fig. 2.

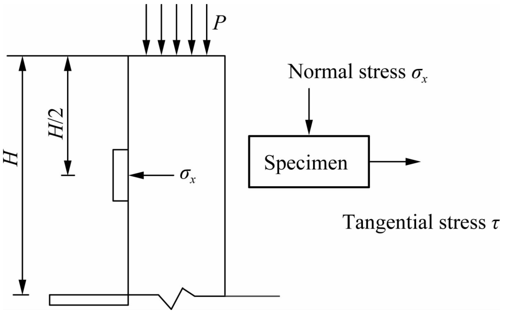

Fig. 2 The diagram of the normal stress calculation

σ_1 is the lateral stress caused by the self-weight of soil. Generally, the soil self-weight stress σ_y is regarded to be a linear distribution with the depth. The stress value at the middle point of thickness is taken as the lateral stress of this layer, and it is also the normal stress σ_1 in the analogue test method. The calculation formula is

$$\sigma_1 = \frac{\mu_1}{1-\mu_1}\sigma_y \tag{1}$$

$$\sigma_y = \sum_{i=1}^{n}\gamma_i h_i + \frac{1}{2}\gamma_n h_n \tag{2}$$

where μ_1 is Poisson's ratio of soil; γ_i, h_i are the bulk density and thickness of the middle point of the first layer, respectively; and γ_n, h_n are the bulk weight and the thickness of the layer at the middle point of the n-th layer, respectively.

σ_4 is the lateral soil pressure under ultimate loads, and it can be calculated as

$$\sigma_4 = \frac{\mu_2}{1-\mu_2}\sigma_y \tag{3}$$

where μ_2 is Poisson's ratio of concrete and σ_y is the axial stress of the pile at the midpoint of each layer.

σ_2, σ_3 and σ_5 can be obtained by linear interpolation of σ_1 and σ_4 as

$$\left.\begin{aligned}\sigma_2 &= \sigma_1 + \frac{\sigma_4-\sigma_1}{3}\\ \sigma_3 &= \sigma_2 + \frac{\sigma_4-\sigma_1}{3}\\ \sigma_5 &= \sigma_4 + \frac{\sigma_4-\sigma_1}{3}\end{aligned}\right\} \tag{4}$$

1.2 Self-balanced loading test

In the self-balanced loading test, the vertical bearing capacity of the pile can be measured by loading a special load cell near the pile tip to motivate the upper and lower parts of the pile at the same time. The pump placed on the ground is used to pressurize the load cell. With the increase in the pressure, the load cell can be separated simultaneously, which will motivate the development of pile side friction and pile tip resistance (see Fig. 3). The pressure of the load cell is measured by pressure gauges on both sides. The axial force at each section of pile and the frictional resistance can be obtained by the reinforcement gauges.

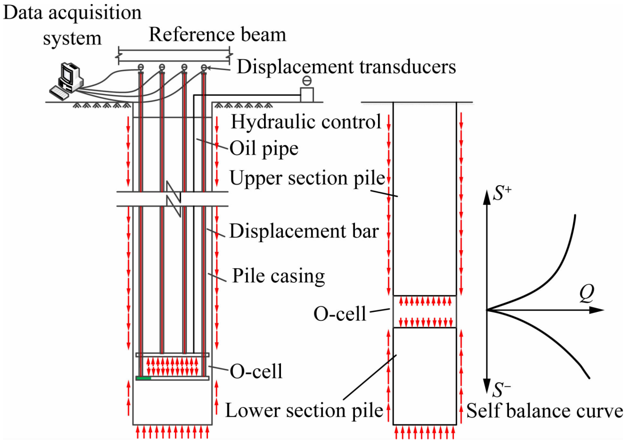

Fig. 3 Self-balanced test method of pile bearing capacity

2 Comparison Test

In order to verify the feasibility of the side friction determined in the analogue test, the project of the Guxiangdi Songhua River Bridge[16] is studied and the comparison results are given by the anchor pile method and analogue test method. The side friction of the pile is determined and the validity of simulation test results is verified.

2.1 Geotechnical conditions

The Guxiangdi Songhua River Bridge is located at the south bank of the Songhua River in Daoli District, Harbin City. The soil profile near the test pile from top to bottom is filled with soil, silty clay, fine sand, coarse sand, medium sand, gravel sand and silty rock. As shown in Fig. 4, the geological conditions of the site are relatively

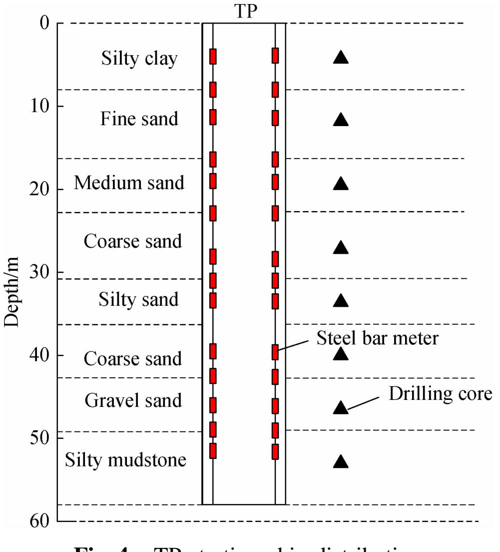

Fig. 4 TP stratigraphic distribution

simple, and the soil is mainly sandy soil. According to the design requirements, the ultimate bearing capacity of the test pile (TP) is determined by the anchor pile method, and is sampled in each layer for the laboratory analogue test. The sampling point site is shown in Fig. 6. According to the code[15], the sample of the soil test is used to ensure that the analogue test is consistent with the field test.

2.2 Analysis of test results

Wang[14] pointed out that in the analogue test method, normal stress can be determined by three methods, soil self-weight, finite element analysis and self-weight loading coupling. Therefore, the normal stress on the side of the pile is determined by the soil self-weight in this paper. This paper focused on the pile side friction, hence, the change value of the side friction in the anchor pile test and self-balanced test will be compared with that of the analogue test method. The value of the pile side friction is related to the relative displacement of the pile-soil interface, which takes a maximum value at a very small displacement level. The ultimate side friction of different pile test methods is shown in Tab. 1.

Tab. 1 Pile side friction value of the anchor pile method and analogue test method

Soil layer	Bottom elevation/m	Side friction/kPa		Recommended value
		Anchor pile method	Analogue test method	
Silty clay	59.00	38.0	17	20
Fine sand	61.97	56.5	43	40
Medium sand	68.47	57.0	53	50
Coarse sand	74.87	55.0	52	60
Silty clay	80.37	62.5	68	50
Coarse sand	82.87	79.5	70	80
Gravel sand	88.37	73.0	171	90
Silty mudstone	103.17	66.5	139	120

The side friction of the pile measured by the anchor pile method is the largest. The side friction of the pile measured by the analogue test is close to the recommended value of the geological exploration report. The reason is that the load is applied to the pile top in the anchor pile. The development of shaft resistance from top to bottom and relative displacement at the upper pile reaches the maximum value more quickly than the lower part of the pile. The soil sample in the analogue test method is from the upper layer of soil, where the self-weight stress of the soil is smaller than that of real project. Therefore, the pile-soil normal stress is smaller, resulting in a smaller value of side friction.

The maximum shaft resistance of the pile in the same soil layer in the middle and upper pile sections obtained by the anchor pile method and analogue test method are similar, and the relative errors range from −5.77% to 11.9%, which indicates that the simulation test is an effective method to determine the pile side friction.

The maximum shaft resistance of the pile at the same soil layer near the pile base is much more different between the anchor pile method and the analogue test method. The latter has larger values of side friction. In addition, the value obtained by the analogue test method is larger than the recommended value. The reason is that the value of normal stress in the analogue test is larger than that in the anchor pile method, where the lateral resistance is obtained.

Overall, the analogue test method is an effective method for determining the side friction of the pile, and can meet the engineering design requirement. Also, it can facilitate the study of the self-balanced conversion factor.

3 Case Studies

Through the comparative analysis of the analogue test method and anchor pile method, it is shown that the analogue test method is an effective method to determine the side friction of the pile. Combined with the self-balanced test case in the Songhua River area, the results of the pile side friction by the analogue test method and the self-balanced method are compared to determine the conversion factor of sandy soil and weathered mudstone in the Songhua River area, which will provide a reference for the self-balanced test in similar projects in this area.

3.1 Case 1: Longhua Songhua River Bridge

3.1.1 Geotechnical conditions

Longhua Songhua River Bridge is located in the northwest of Jilin Province, Songyuan City, at the lower reaches of the Songhua River. The cast-in-place pile foundation system is widely used in this bridge. The soil profile in this site has eight major soil layers, including 5-m-thick fine sandy soils for the uppermost fill layer, a 7.5-m-thick coarse sand, a 26.2-m-thick low liquid limit clay layer, a 13-m-thick medium sandy soil layer, a 3.8-m-thick fully weathered rock layer, and strongly or medium weathered rock.

In this test, the self-balanced test was carried out in three piles, and the simulation test was conducted for taking samples from boreholes near the test piles. The ultimate side friction of the pile from the two test methods was compared. The length and diameter of three piles are 65 and 2 m, respectively.

3.1.2 Analysis of test results

According to the requirement of the self-balanced test method, the steel-bar meters were set between soil layers in the pile body, and several steel-bar meters were set in the thick soil layer to measure the strain of the pile body. Finally, the axial force along the pile length, the shaft resistance and the relative displacement at the pile-soil interface are measured by steel-bar meters. The ultimate side friction of the pile side is usually determined according to the relative displacement curve of the pile side, and the side friction of each pile is shown in Fig. 5(a), Tab. 2 and Tab. 3. There is no significant difference in the value of the side friction between SZ1 and SZ3. Compared with other test piles, the side friction of SZ2 are much more different in Tab. 2. It is due to the borehole collapse in the process of pile construction, which results in the decrease in the bearing performance of the test pile and affects the exertion of the pile side friction. This also indicates that the pile construction method has a great impact on the side friction of the pile.

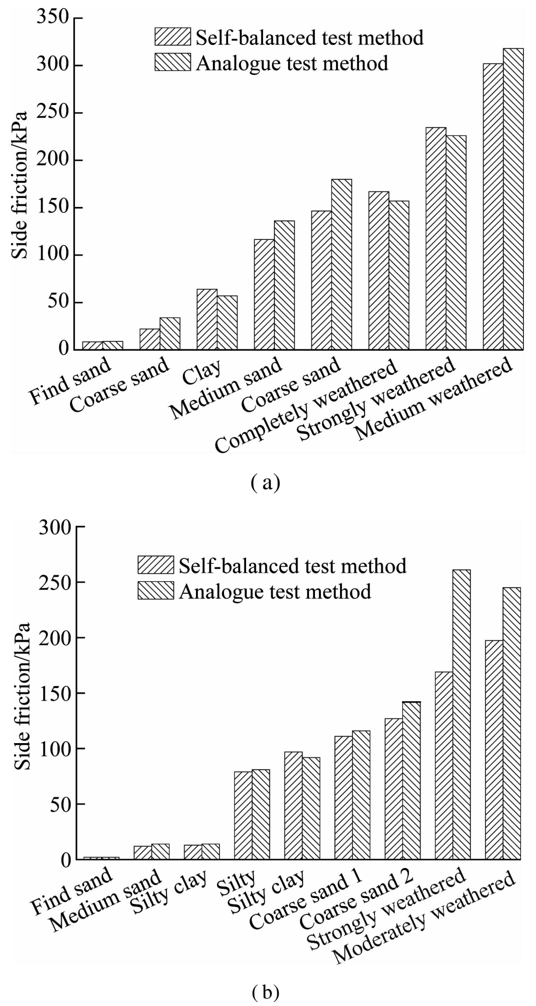

Fig. 5 Side friction comparison of different methods. (a) Longhua Songhua River Bridge; (b) Ningjiang Songhua River Bridge

Tab. 2 Side friction of pile by self-balanced method in Longhua Songhua River Bridge

Soil layer	Side friction/kPa		
	SZ1	SZ2	SZ3
Fine sand	8	23	9
Coarse sand	23	60	21
Low liquid limit clay	74	106	54
Medium sand	121	185	112
Gravel sand	153	199	140
Completely weathered rock	173	433	161
Strongly weathered rock	190	272	279
Medium weathered rock	268	379	336

Tab. 3 Side friction of pile of two methods in Longhua Songhua River Bridge

Soil layer	Side friction/kPa		Conversion factor
	Self-balanced method	Simulated test method	
Fine sand	8.5	9	0.94
Coarse sand	22	34	0.65
Low liquid limit clay	64	57	1.12
Medium sand	116	136	0.86
Gravel sand	147	180	0.81
Completely weathered rock	167	157	1.06
Strongly weathered rock	234	226	1.04
Medium weathered rock	302	318	0.95

Through the field drilling sampling, collecting concrete samples and drilling mud for the laboratory medium direct shear test, the side friction of the pile is determined by reasonable normal stress. As collapse occurred in SZ2, no analysis is made here. The average side friction of the SZ1 and SZ3 piles at the same site is compared with that of the analogue test, as shown in Fig. 5(a). It can be seen that the variation trend of the pile side friction at each soil layer is the same, the side friction is a nonlinear distribution with the increase of soil depth, and the value of the side friction of the coarse sand layer in the middle of the soil layer makes a great difference. The error is around −35%.

The analogue test method is based on the limit equilibrium theory of soil. The side friction by the analogue test method is greater than that of the self-balanced method. From the above analysis, the value of the pile side friction of the analogue test method is close to that of the anchor pile method. It is shown that the self-balanced conversion factor can be obtained by comparing the results of the analogue test method with that of the self-balanced method. The conversion factor of different soil layers is shown in Tab. 3. The conversion factor of sandy soil determined by the analogue test method is 0.65 to 0.86, which is similar to that suggested in Ref. [7] with the range of 0.6 to 0.7. The conversion factor of rock is 0.95 to 1.06, and recommended to be 1.0 in engineering.

3.2 Case 2: Ningjiang Songhua River Bridge

3.2.1 Geotechnical conditions

The displacement of Ningjiang Songhua River Bridge is located in the northwest of Jilin Province. The test pile length and pile diameter are 71.2 and 2.5 m, respectively. The soil profile in the site consists of seven major soil layers: 4.7-m-thick fine sandy soils, a 10-m-thick medium sand layer, a 7.85-m-thick silty-clay layer, an 8.4-m-thick fine sand layer, a 1.25-m-thick silty-clay layer, a 26.5-m-thick coarse sand layer and the strongly or weakly weathered rock. The geological conditions in this area are mainly sandy soil and rock. The self-balanced method and analogue test method are also used to determine the side friction of the pile in this area, and then conversion factors of sandy soil and weathered mudstone are determined.

3.2.2 Analysis of test results

The same method as above was used to carry out the analogue test, and the side friction of the pile determined by the self-balanced method and the analogue test method is compared, as shown in Fig. 5(b) and Tab. 4. There is a great difference in the side friction of the pile at different soil depths, and the variation is nonlinear in general. The side friction difference between the two methods is about 10%. As the side friction of the pile near the bearing layer is not up to the limit state, there is a certain difference with that in the analogue test value. The measured conversion factor of sandy soil in this project is 0.86 to 1.0, which is larger than that of Refs. [7, 17], and the value in code is over conserved. Thus, the range in the code should be amended based on practical application. As the side friction of the pile in strong weathered mudstone is not fully developed, the measured conversion factor is relatively small in this project.

Tab. 4 Side friction of pile of two methods in Ningjiang Songhua River Bridge

Soil layer	Side friction/kPa		Conversion factor
	Self-balanced method	Simulated test method	
Fine sand	2	2	1.0
medium sand	12	14	0.86
Silty clay	13	14	0.93
Fine sand	79	81	0.98
Silty clay	97	92	1.05
Coarse sand 1	111	116	0.96
Coarse sand 2	127	142	0.89
Strongly weathered rock	169 (Not reaching the limit)	261	0.65
Weakly weathered rock	197.46 (Not reaching the limit)	245	0.81

In summary, compared with the results of the bridge pile foundation in Songhua River area, the conservation factor determined by the analogue test method is greater than that of the existing literature and codes, and the conversion factor of various kinds of sandy soils is different due to different soil properties. In order to ensure the safety of the engineering design, it is suggested that the conversion factor of sandy soil should be 0.65 to 0.85, and that of weathered mudstone should be 1.0.

4 Conclusions

1) Comparison results show that the method of determining the side friction of pile by the analogue test method is feasible, and the results from the analogue test method is similar to that of the anchor pile method.

2) Combined with two bridge test cases in the Songhua River area, the conversion factor of the side friction of

self-balanced pile is calculated by the analogue test method. Results show that the value of sandy soil in the code is over conservative, the range of conversion factor of sandy soil is 0.65 to 0.85 and that of weathered mudstone is 1.0.

3) Due to the influence of construction and geological conditions in engineering practice, the results are discrete and should be accumulated in practice so as to obtain a reasonable value range for the conversion factor.

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基于模拟试验法的钻孔灌注桩自平衡试验转换系数分析

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摘要:基于桩土相互作用特性,以 Mohr-Coulomb 强度理论为依据,提出了一种室内模拟试验法确定桩侧摩阻力的新方法. 结合实际工程案例,对比传统锚桩法和自平衡法,验证了模拟试验法确定桩侧摩阻力的有效性. 以松花江地区桥梁桩基自平衡试验为例,采用模拟试验法确定该地区砂性土和风化泥岩的转换系数,结果表明,松花江地区砂性土和风化泥岩的转换系数应综合考虑地质条件、施工工艺等因素,规范取值相对保守,建议工程应用做适当修正;该地区砂性土转换系数建议取值范围为 0.65 ~0.85,风化泥岩取 1.0.

关键词:钻孔灌注桩;自平衡法;模拟试验法;Mohr-Coulomb 强度理论;转换系数

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