

## Research Article

# **Research on Test Method of Foundation Bed Coefficient in Nanjing Soft Soil Area**

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Relying on the geotechnical engineering survey project of Nanjing Lukou Airport, this research adopts the method of combining in situ and indoor testing to analyze the coefficient of soil foundation under different conditions (flow plastic, plastic, and soft plastic). Based on the differences in test results, in situ and indoor test methods appropriate for the benchmark bed coefficient of Nanjing soft soil area are proposed. Research findings depicted that the bed coefficients obtained by different methods are not similar; therefore, if the data obtained by different methods need to be compared and analyzed, they have to be unified as  $K_{30}$ . Simultaneously, in the indoor test, this study compared the foundation bed coefficient obtained by the consolidation method, the improved  $K_0$  instrument consolidation method, and the triaxial method. Results revealed that the improved  $K_0$ instrument consolidation method can better realize the test of the soil foundation coefficient. This study can provide a reference for geotechnical investigation and design of soft soil in the study area.

#### 1. Introduction

The foundation bed coefficient is an important parameter in the design of underground engineering such as foundation pit enclosure and underground rail transit; therefore, it is critical to determine its value [1-5]. As an inherent mechanical property index, the coefficient of the foundation bed is determined by the properties of soil. Regarding the experiment of the foundation bed coefficient and the discussion of the value method, a lot of experimental research work has been carried out. For example, Sandu et al. [6] deduced the calculation of the lateral foundation bed reaction coefficient based on the working mechanism of the flat shovel side expansion instrument formula. Corrêa-Silva et al. [7] combined the geotechnical survey of Wuhan light rail and compared the foundation bed coefficient consolidation method and the triaxial method. Shen et al. [8] used a flat shovel side dilatometer to test and study the horizontal bed coefficient of coastal sedimentary soft soils. Based on indoor consolidation test and triaxial test, Wang et al. [9] used the size correction empirical formula to correct the bed coefficient directly determined by the indoor test. Ren et al. [10] deduced the calculation formula of the bed coefficient with the compressive modulus as a known parameter and compared it with the empirical value given by the specification. At present, in geotechnical engineering surveys, in situ tests such as  $K_{30}$ plate load test, spiral plate load test, side pressure test, and flat shovel side expansion test as well as indoor consolidation method and triaxial method are mainly employed to test the bed coefficient [11–18]. However, due to the influence of test equipment and sample size, the values obtained by different test methods are quite different [19-23]. In actual work, the Terzaghi correction formula is often used to correct the diameter of the  $K_{30}$  flat load plate diameter as the standard [24-28]. Finally, the value of the soil foundation bed coefficient is proposed in conjunction with the experience value.

Previous research indicates that the bed coefficient was primarily used for comparing the flat shovel side expansion test, indoor consolidation, and triaxial test [29–32]. It was rarely verified with the benchmark value of the  $K_{30}$  test, and there was no related test using the  $K_0$  instrument. To

compensate for these shortcomings, this article analyzes various test methods and improves the limitation that the previous  $K_{30}$  device can only obtain the vertical bed coefficient and realizes the test of the horizontal bed coefficient by this device, based on the geotechnical engineering investigation project of Nanjing Lukou Airport. At the same time, the  $K_0$  instrument is modified and developed and then compared with other indoor tests (such as indoor consolidation method and triaxial method). The improved  $K_0$  consolidation method can better realize the test of soil base coefficient. An in situ test and laboratory test method suitable for the benchmark subgrade coefficient in Nanjing soft soil area is proposed based on the analysis data of Nanjing soft soil in situ test and laboratory test and relying on the related theory of soil mechanics. This research can be used to guide geotechnical investigations and foundation design in the Nanjing soft soil area.

#### 2. Engineering Geological Conditions

As shown in Figure 1, Nanjing is located in the east of China, the lower reaches of the Yangtze River. It is located along the Yangtze River and has a developed water network, which makes the soft soil of lagoons and river alluvial deposits widely distributed. These soft soil layers are usually mud and silt soil, which are characterized by high water content, low strength, high compressibility, poor permeability, uneven soil quality, and great differences between regions. The test site of this study is located in Lukou International Airport in Jiangning District, southeast Nanjing. The test site has a single topography and is a coastal alluvial plain. The sedimentary types are mainly Quaternary marine soft soil layers. According to the survey report combined with the on-site drilling situation, the foundation soil within the survey depth range is divided into 7 engineering geological layers from top to bottom with regard to the geological age. Table 1 depicts the distribution and physical and mechanical properties of each soil layer.

In this study, the upper plastic (hard shell layer), lower flow plastic, soft plastic, and plastic clay soil foundation coefficients were tested and analyzed in conjunction with the engineering geological conditions and the physical and mechanical properties of the soil.

In Table 1,  $\omega$  is water content,  $\gamma$  is the gravity of soil,  $e_0$  is the pore ratio,  $I_{\rm P}$  is the plasticity index,  $I_{\rm L}$  is the liquid index, and  $E_{\rm s1-2}$  is the compression modulus.

#### 3. Test Plan Design

Due to the geotechnical engineering conditions of the soil in the study area, in situ test methods such as  $K_{30}$  plate load test, flat shovel side expansion test, indoor consolidation method, improved  $K_0$  instrument consolidation method, and triaxial method were adopted. In combination, test and analysis were carried out on soils in various states (flow plastic, plastic, and soft plastic) widely distributed in Nanjing.

#### 3.1. In Situ Test

3.1.1.  $K_{30}$  Load Test. In Chinese rail transit engineering and railway engineering, the  $K_{30}$  load test is often used as a direct

method to determine the coefficient of the foundation soil, which is based on the load test results under the condition of a 30 cm diameter circular plate. As shown in Figure 2, 6 test points are arranged near the corresponding in situ test and sampling holes in the test site. The  $K_{30}$  plate load tester is used to plasticize the upper part of the test depth. Clay (hard shell layer) is tested for bed coefficient. This test uses a balance beam to pressurize, a truck to provide a reaction force, and an improved back wall to provide a reaction force in the horizontal bed coefficient test.

During the test, the load plate is placed on the flat test point, and the truck matching the test is driven to a place less than 1 m away from the test site, making the rear beam of the truck located directly above the load plate. The jack is placed on the load plate and the measuring bridge is installed, and the jackscrew is turned so that it is in contact with the truck reaction beam. Then, the dial indicator is also installed making the dial indicator rod fall vertically to the load measuring point. The increment of 0.04 MPa was applied step by step to record the amount of subsidence of each stage of load. When the load intensity exceeded the estimated actual contact pressure in situ or reached the yield point of the foundation, the test would stop.

3.1.2. Side Expansion Test of a Flat Shovel. In this test, the ETU-G1-type flat shovel side swelling tester is used and two test points are arranged to test the horizontal subgrade coefficients of the flowing plastic, soft plastic, and plastic soil on the hard shell layer and its lower part. As depicted in Figure 3, during the test, the flat shovel side expansion test probe is pressed into the soil with TMU-9C static penetration testing equipment. After achieving the predetermined depth, air is injected to expand the steel membrane on the flat shovel probe laterally, and then, the pressure values of lateral expansion of the membrane at different distances were measured, respectively (0.05 mm and 1.10 mm). Finally, the physical and mechanical properties of the foundation soil are calculated using a formula based on the relationship between the measured pressure and membrane deformation [33-54].

#### 3.2. Indoor Test

3.2.1. Test Plan. Indoor tests on thin-walled soil samples collected on-site are conducted using the consolidation method, improved  $K_0$  instrument consolidation method, and triaxial method.

3.2.2. Test Method. Indoor tests were conducted by consolidation method,  $K_0$  instrument consolidation method, and indoor triaxial test, and test samples were prepared for each method in advance; the specific sample size of the tests can be seen in Table 2.

(1) Consolidation Method. In the test, a ring knife with an inner diameter of 61.8 mm and a height of 15 mm was used to take soil samples and placed them into the WG-type consolidation instrument (see Figure 4(a)); both ends of the soil sample are pasted with filter paper. Pressure guide rings, plates, and directional steel balls were installed on the soil



FIGURE 1: Geographical location of the test site.

TABLE 1: Foundation soil distribution and physical and mechanical properties index.

Layer number	Lithology name	Soil thickness (m)	Soft plastic	ω (%)	$\gamma$ (KN/m <sup>3</sup> )	$e_0$	$I_{\rm P}$	$I_{\rm L}$	<i>E</i> <sub>s1-2</sub> (MPa)
1	Fill soil	0.4-0.6	/	/	/	/	/	/	/
2	Clay	0.7-2.6	Plastic	28.3	16.3	1.21	16.98	0.52	3.63
3	Silty powdered clay	4.0-11.9	Flow plastic	41.3	15.2	1.12	17.32	1.23	2.65
4	Silty clay	5.8-12.6	Flow plastic	40.6	15.9	1.35	14.36	1.13	1.69
5	Clay	4.9-9.8	Soft plastic	47.3	15.4	1.24	18.65	1.03	1.98
6	Powdered clay	2-4.6	Plastic	29.8	17.2	0.61	19.32	0.65	1.75
7	Round gravel	>5.3	Compact	/	/	/	/	/	/



FIGURE 2:  $K_{30}$  plate load tester.

sample, and the joints of each were checked whether the part-turn is flexible and then balances the pressurized part. After the cross beam contacts with the ball column, the piston rod and the micrometer were installed and adjusted to zero. The vertical pressure level is 12.5, 25, 50, 100, 200, and 400 kPa, and the degree of each level of load is recorded after 10 minutes; the reading is accurate to 0.01 mm. The curve corresponding to  $25 \sim 50 \text{ kPa}$  is used as the value interval of the bed coefficient.

(2)  $K_0$  Instrument Consolidation Method. As shown in Figure 4(b), the container of the ETU-G1  $K_0$  instrument is used to replace the consolidation container of the horizontal bar consolidation instrument, the pressure frame matching the  $K_0$  instrument container is reassembled, and the displacement sensor for measuring displacement is mounted on the pressure frame to perform the basic indoor test of bed coefficient.

Before the  $K_0$  consolidation instrument was used, air bubbles in the closed chamber and side pressure system were removed, and the sealing of the closed chamber and pipeline system was checked. The undisturbed soil sample was cut with a ring knife with an inner diameter of 61.8 mm and a height of 40 mm and pushed into the  $K_0$  consolidation instrument's container. The upper side pressure sensor was installed, and then, air bubbles in the compression chamber and piping system were gushed out. Also, the pressure frame and displacement sensor are installed. A prepressure of 1 kPa was applied to make contact between the sample and the upper and lower parts of the instrument, and the displacement sensor was adjusted to an appropriate position. The acquisition and processing software were opened to configure the test parameters



FIGURE 3: Side expansion test of a flat shovel.

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Testing method	Height (mm)	Radius (mm)	The ratio of height to radius
Consolidation method	15	25.5	0.59
<i>K</i> <sub>0</sub> consolidation method	30	25.5	1.18
Triaxial method	45	17.3	2.60

(pressure levels, data collection time, etc.). Vertical pressures of 25, 50, 75, 100, 150, 200, 300, and 400 kPa were applied, respectively, till the end of the test. The P-S curve of the indoor test is close to a straight line at the initial stage, and the secant modulus is used to estimate the bed coefficient at the soil sample sinking amount of 1.25 mm.

(3) Indoor Triaxial Test. As shown in Figure 4(c), the triaxial test adopts a cylinder sample with a diameter of 25.5 mm and a height of 45 mm for testing. Firstly, the sample is loaded into the vacuum saturation device for saturation, and then, pressure is applied on the three coordinate directions of the sample in space, carrying out a consolidation drainage test (CD) at the state of  $K_0$ . The stress path is taken as  $\Delta\sigma_3/\Delta\sigma_1 = 0$ , 0.2, 0.3, and 0.3 independently, until the specimen is destroyed. Finally, take the secant modulus at  $\Delta\sigma_3/\Delta\sigma_1 = 0.3$  and deformation S = 1.32 mm (strain 1.76%) as the bed coefficient.

#### 4. Test Results and Discussion

4.1. Comparative Analysis of Test Data. According to different test schemes, the numerical values obtained are analyzed separately according to the depth of the soil sample and its physical state (plasticity, flow plasticity, soft plasticity, and plasticity), and the numerical analysis of the bed coefficient adopts the mean value. The statistics of actual measured values of soil foundation bed coefficient under each test method are shown in Table 3. It can be seen from Table 3 that there are large differences in the coefficient of foundation soil under the same geological conditions, and the ratio of the maximum value to the minimum value is 1.5 to 5.3. Take the following plastic silty clay test results as an example. The vertical bed coefficient obtained by different test methods is in the range of 94.3~195.3 MPa/m, and the difference between the maximum value and the minimum value is nearly 2.1 times. Comparing the empirical value range from 18 to 40 MPa/m, the results are also several times different. As a result, if a unified value standard is not used, the results of various test methods cannot be directly applied in design.

4.2. Diameter Correction. Terzaghi believes that the bed factor is related to the size of the load board. Therefore, the bed factor directly measured by load boards of different sizes and indoor samples is corrected to the on-site  $K_{30}$  value (D = 30 cm load board). It can be modified according to the following formula:

To sandy soils,

$$K_{30} = \frac{(2B)^2}{(B+0.3)^2} K.$$
 (1)

To cohesive soil,

$$K_{30} = \frac{B}{0.3}K,$$
 (2)

where *B* is the diameter or width of the load plate and *K* is the base bed coefficient value measured directly.

Considering the influence of the size effect, after diameter correction, the correction values of soil bed coefficients in different states are listed in Table 3. The in situ test is carried out on the plastic-like hard crust that is common on the surface of the soft soil area in Nanjing. Based on the most direct and effective  $K_{30}$  plate load test, the vertical base bed coefficient obtained is greater than the indoor test method after the diameter correction. The value is consistent with the in situ test value of the flat shovel side expansion and is close to the upper limit of the empirical value; the indoor test value is significantly smaller than the in situ test value. The analysis shows that the value of the base bed coefficient after the diameter correction tends to be the same for the in situ test, but the value obtained after the diameter correction differs significantly between the in situ test and the indoor test.

The bed coefficients obtained by the indoor triaxial method after diameter correction are low, which is inconsistent with the physical and mechanical properties of the soil, mainly because the sample size employed in the indoor triaxial method is  $39.1 \text{ mm} \times 80 \text{ mm}$ . Although the height is relatively large, its diameter is relatively small. Due to the limitation of the engineering characteristics of the soft soil, the disturbance is relatively large when the sample is made indoors, and the value is relatively low; for the clayey soil in the plastic state, the physical and mechanical properties of face sedimentary soil are better than the upper hard crust layer due to the lower land, so its value is slightly larger than it, but the values of both are generally smaller than the



(a) Consolidation instrument

(b)  $K_0$  instrument



(c) Triaxial instrument

FIGURE 4: Indoor test apparatus.

TABLE 3: Measured and corrected values of bed coeffic
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m et al l	Plastic (hard shell layer)		Flow molding		Soft plastic		Plastic	
lesting method	Vertical	Level	Vertical	Level (MP	Vertical Pa/m)	Level	Vertical	Level
K <sub>30</sub>	30.1	23.6	/	/	/	/	/	/
Flat shovel side expansion method	/	123.2	/	62.1	/	113.6	/	150.3
$K_0$ consolidation method	69.8	71.2	42.3	40.2	60.2	56.3	80.3	80.3
Consolidation method	165.3	/	68.2	/	125.5	/	180.5	/
Triaxial method	62.3	75.6	15.3	20.3	21.3	25.1	90.2	96.5
Maximum/minimum (measured value)	3.6	5.3	2.3	1.8	3.5	3.5	1.8	1.5
Specification recommended value	12-22	10-26	2-11	2-8	6-18	10-21	15-38	18-40

empirical value, which is also related to the degree of artificial disturbance in the sample preparation process.

Table 4 depicts the vertical bed coefficients obtained by the  $K_0$  instrument consolidation method and consolidation method after the diameter correction in different conditions. Also, for the same geological conditions, the ratio of the vertical bed coefficients obtained by the two consolidation methods is 1.2 to 2.46, which is close to 2.5, and its value is app ratio 1/2 relation which is approximately inversely proportional to the sample heights hip. The analysis demonstrates that diameter correction of the bed coefficients obtained by the two consolidation methods is impossible, and the effect of sample height on test results should be considered concurrently.

Testing method	Plastic	Flow molding	Soft plastic	Plastic	Sample size (mm)
Consolidation method	32.1	14.2	21.3	34.63	15 * 45.5
$K_0$ consolidation method	12.3	9.3	16.4	15.24	30 * 45.5
Triaxial method	1.85	1.2	1.85	2.46	/

TABLE 4: Comparison of vertical bed coefficients of different methods.

#### 5. Conclusion

Relying on the geotechnical engineering survey project of Nanjing Lukou Airport, this study adopts the method of combining on-site in situ testing and indoor testing to test and analyze the coefficient of soil foundation under different conditions (flow plastic, plastic, and soft plastic). According to related theories, the standard of the base bed coefficient is compared and analyzed, and the in situ test and indoor test methods suitable for the benchmark bed coefficient of the Nanjing soft soil area were proposed.

It is found that the bed coefficients (vertical, horizontal) obtained by different test methods, due to the influence of the size effect, the bed coefficients of the same foundation soil are very different, so they must be unified to  $K_{30}$ . Secondly, in the indoor test, the improved  $K_0$  instrument consolidation method can better realize the test of the soil foundation coefficient. Finally, due to the limitation of the sample size, the triaxial test is easy to cause damage to the soft soil during the sample preparation process. Larger disturbances result in a significantly lower value of the base bed coefficient, so the soft soil should be avoided as much as possible when making samples.

#### **Data Availability**

The data are generated from experiments and can be available from the corresponding author upon request.

#### **Conflicts of Interest**

The authors declare that there are no conflicts of interest regarding the publication of this paper.

#### **Authors' Contributions**

Zhang Min carried out the experiments, analyzed the results, conducted the theoretical explanations, and wrote the manuscript. Qiu Tao provided constructive guidance for the thesis, and we revised the thesis in writing.

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