

# Method for Determining Foundation Bearing Capacity Based on Pressuremeter Test Curve

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**Abstract.** The pressuremeter test is a horizontal in-situ load test that can objectively reflect the lateral strength and deformation characteristics of the tested soil. The existing methods for determining the characteristic values of foundation bearing capacity through pressuremeter tests are mainly based on the pressure values corresponding to the starting and ending points of the straight line part of the lateral pressure load deformation curve, which has significant uncertainty. Based on the characteristics of the p-s curve, this article uses a cubic polynomial to fit the p-s curve, and the goodness of fit is greater than 0.99; gives a method for determining the characteristic values of foundation bearing capacity based on the pressure value at the inflection point of the p-s curve; and obtains the bearing capacity of the silty clay layer and the fine sand layer in the depth range of 46.0 meters. The calculation results show that compared with the near line method, the relative error of the bearing capacity characteristics of the foundation is within 20%, which can meet the engineering needs. This provides a new approach for determining the bearing capacity of foundations through lateral pressure tests.

**Keywords:** Pressuremeter test; Load deformation curve; Curve fitting, Fondation bearing capacity.

## 1. Introduction

The pressuremeter test uses a pressure gauge probe to apply lateral horizontal pressure to the pre-drilled hole wall, causing the hole wall to expand outward until it is destroyed, thereby obtaining the relationship between pressure and the increment of drilling volume, as well as the relationship between pressure and lateral deformation. Based on this, an in-situ testing method is used to determine the mechanical properties of the foundation soil [1,2].

The pressuremeter test was initially proposed by German engineer Kogler in the 1930s, and was applied in engineering by French engineer Ménard in 1957. After years of development, it has been widely used in countries such as Europe, America, and Japan. In the early 1960s, China introduced lateral pressure testing from overseas and accumulated rich experience[3]. The pressuremeter test method is simple and rapid. Compared with indoor geotechnical tests, it does not have the disturbance process of soil sampling; Compared with in-situ testing methods such as probing, it can obtain the relationship between pressure and volume changes of columnar pores during the entire expansion process; Compared with the pressure plate load test, it can explore the mechanical properties of soil layers at different depths [4-7]. Yang Chao, Wang Ren, etc. conducted in-situ tests using a pressure gauge at the mouth of the Yangtze River and obtained the variation patterns of various parameters in the pressure gauge test[8]. Wang Mingyuan, Shan Zhigang, etc. used land in-situ comparative tests to modify the calculation method of calculating geological design parameters through lateral pressure tests, and compared and verified it with offshore lateral pressure tests, cross plate shear tests, and standard penetration tests [9]. Wang Jin, Zhu Zeqi, etc. investigated the in-situ mechanical properties of soft soil sites through self drilling lateral pressure tests, and obtained mechanical indicators such as in-situ horizontal stress, temporary plastic pressure, undrained shear strength, and shear modulus of soft soil layers in the depth range of 29.0 meters[10]. Yang Yusheng, Liu Xiaosheng, etc. conducted in-situ pressuremeter tests on the deep silty clay of the covering layer, measured its load displacement curve, and determined the mechanical index characteristic values such as initial pressure, bearing capacity characteristic values, and pressure modulus at the corresponding depth [11]. Huiyuan, Dai Guoliang, etc. obtained a direct method for predicting the bearing capacity of pile foundations using the pressuremeter test

through a three-stage linear classification. Compared with European standards and highway bridge and culvert standards, this method is more suitable for predicting the bearing capacity of pile foundations in deep sandy soil[12]. Zhao Zhenguo, Liu Zhiqing, etc. proved that obtaining the bearing capacity of soft rock foundation through high-pressure pressuremeter test is feasible and effective by comparing the recommended values in the specifications with the results of on-site in-situ load tests[13]. In current research, the initial pressure  $p_0$  and critical plastic pressure  $p_f$  of the pressuremeter test are determined by the starting and ending points of the straight segment of the  $p$ - $s$  curve. Engineering practice has shown that there are almost no straight sections of the lateral pressure curve, and the soil is a typical elastic-plastic material. In theory, strict straight sections do not exist. This brings difficulties to the determination of  $p_f$  and significant randomness. Therefore, based on the load deformation results of the pressuremeter test at a certain political engineering site in Nanjing, this article proposes an approximate method for calculating the bearing capacity of the foundation based on the  $p$ - $s$  curve, providing a new idea for determining the bearing capacity of the foundation through lateral pressure tests.

## 2. Project Overview

A municipal engineering site in Nanjing has a stable water level buried at a depth of 0.4m-3.5m below ground level. The main soil layers include:

②-2. Silty Clay: gray, soft-flow plastic, containing a small amount of saprophytic plants; The burial depth at the top of the layer is 0.2m-7.8m, and the layer thickness is 7.1m-13.9m;

②-3. Silty silty clay and silty clay: gray, flowing-soft plastic, with developed horizontal bedding, interbedded with thin layers of silt and sand; The burial depth at the top of the layer is 9.8m-19.5m, and the layer thickness is 3.9m-13.4m;

②-4. Silty fine sand mixed with powdery clay: gray, medium dense, soft to flow plastic, locally interbedded. The burial depth at the top of the layer is 22.9m-32.5m, and the layer thickness is 0.5m-8.6m;

②-5. Fine sand: gray, dense, containing mica fragments, partially interbedded with thin layers of powdery clay and shells. The burial depth at the top of the layer is 28.7m-36.2m, and the layer thickness is 4.7m-16.5m. Below it are dense layers of medium to fine sand, strongly weathered argillaceous siltstone, and sandy mudstone.

Table 1. Statistical values of the main physical and mechanical indicators of the soil layer

Item		w /%	$\rho$	e	wL/%	wP/%	IP	IL	a1-2	Es1-2
②-2	N	305	302	302	305	305	303	304	218	218
	$\mu$	38.94	1.78	1.12	37.46	21.95	13.15	1.10	0.68	3.20
	$\delta$	0.09	0.02	0.08	0.08	0.09	0.11	0.13	0.18	0.16
②-3	N	246	233	233	243	243	243	242	175	174
	$\mu$	33.63	1.81	1.01	33.18	20.01	13.17	1.04	0.54	3.95
	$\delta$	0.10	0.02	0.08	0.08	0.08	0.16	0.15	0.25	0.23
②-4	N	135	128	128	63	63	63	63	82	82
	$\mu$	30.4	1.86	0.933	32.8	20.2	12.7	1.05	0.36	6.40
	$\delta$	0.15	0.03	0.13	0.09	0.09	0.18	0.18	0.43	0.42
②-5	N	280	223	223					122	122
	$\mu$	24.1	1.90	1.54					0.14	12.93
	$\delta$	0.15	0.04	0.06					0.20	0.15

Table notes: N is the total number of samples;  $\mu$  is the mean;  $\delta$  is the coefficient of variation; w is the natural moisture content (%);  $\rho$  is the natural density (g/cm<sup>3</sup>); e is the porosity ratio; wL is the liquid limit (%); wP is the plastic limit (%), IP is the plasticity index; IL liquid index, a1-2 is the compression coefficient (MPa-1); Es1-2 is the compressive modulus (MPa).

The statistical values of the main physical and mechanical parameters of the soil layers ②-2~②-5 where the pressuremeter test is conducted are shown in Table 1. It can be seen that the variation coefficients of moisture content, density, porosity, liquid limit, and plastic limit are all less than 0.10. The variation coefficients of plasticity index, liquid index, compression coefficient, and compression modulus are all greater than 0.10. The variation coefficients of compression coefficient are 0.18-0.43, and the variation coefficients of compression modulus are 0.15-0.42.

### 3. Fitting of Load Deformation Curve for pressuremeter Test

Figure 1 shows the  $p-s$  curve and  $p-\Delta s$  curve of the lateral pressure test on the ②-2~②-5 layers of a municipal engineering site in Nanjing. From Figure 1, as the load increases, the radial displacement in the initial stage (Section I) rapidly increases, which is actually the compaction stage after unloading the borehole and applying lateral pressure load; The radial displacement in the quasi-elastic stage (stage II) increases approximately linearly with increasing pressure; The radial displacement during the plastic deformation stage (Section III) rapidly increases with increasing pressure [11].

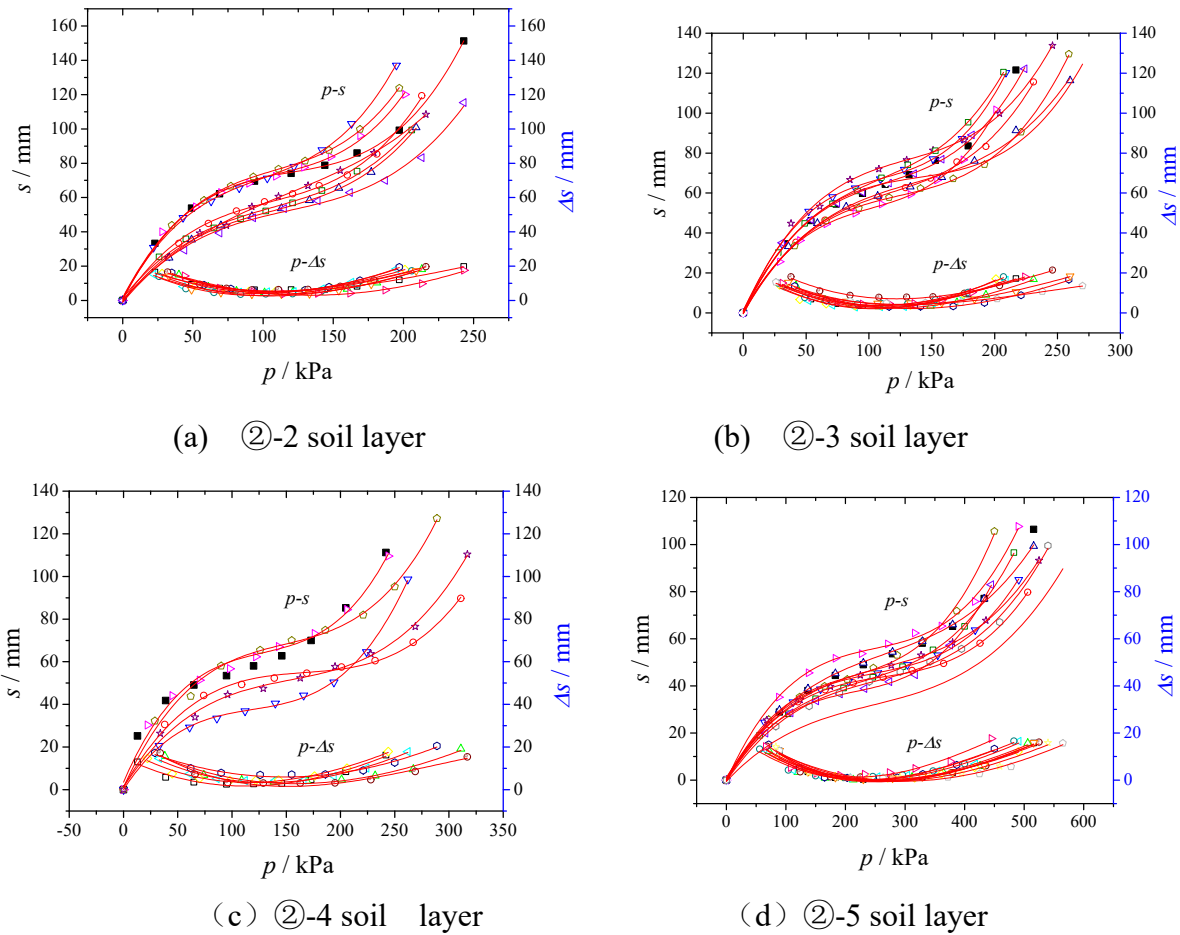


Fig. 1 Fitting  $p-s$  and  $p-\Delta s$  curves for soil pressure tests

From Figure 1, it can be seen that the ideal straight line segment of the  $p-s$  curve does not exist, which gives a difficulties in determining  $p_f$ . The  $p-\Delta s$  curve is a lower convex function, and when  $p$  approaches zero,  $\Delta s/\Delta p$  is the first derivative of the  $p-s$  curve. The characteristics of the  $p-\Delta s$  curve can be approximated as a quadratic function of lateral deformation, therefore it can be assumed that the  $p-s$  curve is a cubic function. It has

$$s = A + Bp + Cp^2 + Dp^3 \quad (1)$$

The pressure value corresponding to the zero point of the second derivative of the lateral deformation  $s$  is:

$$p_{2d} = -C/(3D) \quad (2)$$

Where,  $A$ ,  $B$ ,  $C$  and  $D$  are fitting parameters of Load Deformation Curve  $p$ - $s$ .

The fitting curves of the  $p$ - $s$  for layers ②-2 to ②-5 of the site are shown in Figure 1. It can be seen that the fitting degree of the  $p$ - $s$  curves is high, and the goodness of fit is greater than 0.99. The fitting parameters of the  $p$ - $s$  curve are shown in Tables 1 to 4. The coefficient  $A$  is a constant term.  $A$  is not equal to 0, indicating that the fitted curve is not at the coordinate origin. However, except for a few curves, the absolute value of  $A$  is less than 1.5. When  $p$  is greater than  $p_0$  (initial pressure), the impact on the  $s$  value is less than 5%, and it can be approximated as 0.

#### 4. Determination of foundation bearing capacity by pressuremeter test

Pressuremeter test is a horizontal in-situ load test that mainly applies radial uniform pressure to the soil through a pressure gauge. Based on the obtained pressure radial displacement relationship curve, the characteristic value of soil bearing capacity is obtained. Previous studies have shown that the lateral pressure test is suitable for evaluating the bearing characteristics of soft rock foundations [1]. A large amount of test data shows that the bearing capacity determined by subtracting the static lateral pressure  $p_0$  of the soil layer from the temporary plastic pressure  $p_f$  obtained from the lateral pressure test is basically consistent with the characteristic bearing capacity obtained from the load test. When using the pressuremeter test to determine the characteristic values of foundation bearing capacity in China, the following formula is generally used[1]:

$$f_{aL} = p_f - p_0 \quad (3)$$

The initial pressure  $p_0$  and the critical plastic pressure  $p_f$  are determined by the starting and ending points of the straight segment of the pressure gauge curve. Engineering practice has shown that there are almost no straight sections of the lateral pressure curve, and the soil is a typical elastic-plastic material. In theory, strict straight sections do not exist. This brings difficulties to the determination of  $p_f$  and significant randomness.

According to the characteristics of the  $p$ - $s$  curve, it has a inflection point, where the second derivative of  $s$  is equal to 0 and the corresponding pressure value is  $p_{2d}$ .  $P_0$  is the initial pressure (i.e. the static lateral pressure), which can be determined by the  $p$ - $s$  curve or static soil pressure calculation.

$$p_f = p_0 + 2(p_{2d} - p_0) \quad (4)$$

$$f_{a2D} = p_f - p_0 = 2(p_{2d} - p_0) \quad (5)$$

Table 2.  $p$ - $s$  curve fitting parameters and calculation results for layers ② -2

$z$	$A$	$B$	$C$	$D$	$p_0/\text{kPa}$ $a$	$p_f/\text{kPa}$	$f_{aL}/\text{kPa}$	$p_{2d}/\text{kPa}$ $a$	$f_{a2D}/\text{kPa}$ $\text{Pa}$	R.E. (%)
5	1.31509	1.55105	-0.0117 2	3.24E-0 5	77	150	73	120.51	87.02	16.11
9	-0.7109 7	1.22614	-0.0095 8	3.03E-0 5	70	152	75	105.41	70.82	5.90
13	1.15748	1.53269	-0.0125 7	4.26E-0 5	52	129	77	98.44	92.88	17.10
6	1.6234	1.57192	-0.0125 3	3.82E-0 5	67	146	79	109.46	84.92	6.97
10	0.33227	1.60369	-0.0125 3	3.85E-0 5	63	144	81	108.52	91.04	11.03
14	0.14769	0.90866	-0.0048 4	1.37E-0 5	69	152	83	118.03	98.06	15.36

8	1.38902	1.02114	-0.0073 9	2.31E-0 5	68	152	84	106.51	77.02	9.06
12	-0.5445 8	1.04643	-0.0077 6	2.42E-0 5	66	144	78	106.77	81.54	4.34
16	-1.0570 5	0.99479	-0.0069	1.95E-0 5	70	172	87	117.85	95.7	9.09

Table note: z is The burial depth at the top of the layer, faL represents the bearing capacity determined by the approximate straight line method; fa2D represents the bearing capacity of the foundation calculated based on the pressure value at the inflection point of the p-s curve; The following Table is the same as Table 2.

Table 3. *p-s* curve fitting parameters and calculation results for layers ② -3

z	A	B	C	D	p0/kPa a	pf/kPa	faL/kPa a	p2d/kPa	fa2D/kPa	R.E. (%)
17	0.03086	1.32698	-0.0101 7	3.05E-0 5	62	147	85	111.14	98.28	13.51
21	0.03164	1.12647	-0.0078 2	2.21E-0 5	60	159	99	118.04	116.08	14.71
24	-0.3350 3	1.48544	-0.0118 8	3.60E-0 5	60	155	95	110.03	100.06	5.06
16	-0.4108	1.18877	-0.0098 4	3.20E-0 5	63	149	86	102.36	78.72	9.25
20	-0.3276 5	1.12756	-0.0078 6	2.10E-0 5	68	175	107	124.94	113.88	6.04
24	0.82292	1.3857	-0.0092 5	2.37E-0 5	70	188	118	130.35	120.7	2.24
26	0.25009	1.29267	-0.0093 6	2.86E-0 5	66	155	89	109.08	86.16	3.30
20	1.28285	1.04391	-0.0063 4	1.56E-0 5	68	177	109	135.70	135.4	19.50
22	1.28448	1.2624	-0.0091 9	2.67E-0 5	58	152	94	114.82	113.64	17.28
24	0.64085	1.25254	-0.0082 9	1.98E-0 5	78	180	102	139.32	122.64	16.83

Table 4. *p-s* curve fitting parameters and calculation results for layers ② -4

z	A	B	C	D	p0/kPa	pf/kPa	faL/kPa a	p2d/kPa a	fa2D/kPa	R.E. (%)
28	5.9895 5	1.1172	-0.00831	2.28E-0 5	52	168	116	121.48	138.96	16.52
30	1.3371 7	0.8873 1	-0.00508	1.01E-0 5	98	239	141	167.28	138.56	1.76
30	0.0485 7	0.7828 7	-0.0059	1.66E-0 5	58	182	124	118.79	121.58	1.99
32	3.4984 4	1.1750 4	-0.00819	2.12E-0 5	52	186	134	128.79	153.58	12.75
32	1.2427 0	1.1040 9	-0.0066	1.48E-0 5	69	211	142	148.57	159.14	10.77
34	1.2162 8	0.7822 9	-0.00445	9.66E-0 6	90	235	145	153.53	127.06	14.12

Table 5. *p-s* curve fitting parameters and calculation results for layers ② -5

z	A	B	C	D	p0/kPa	pf/kPa	faL/kPa a	p2d/kPa a	fa2D/kPa	R.E. (%)
32	-0.0485	0.4336	-0.0013	1.82E-0	152	367	215	253.42	202.84	5.99

	3	9	8	6						
36	0.05171	0.4219 7	-0.0014 6	1.85E-0 6	145	370	225	263.34	236.68	4.93
38	0.83812	0.4318 2	-0.0015 2	2.02E-0 6	138	366	228	251.45	226.9	0.48
42	-0.2502 9	0.5643	-0.0020 4	2.72E-0 6	131	362	231	250.03	238.06	2.97
38	1.12049	0.3983 9	-0.0012 6	1.59E-0 6	155	391	236	264.53	219.06	7.73
42	0.22758	0.3933 2	-0.0013 9	2.05E-0 6	123	366	243	226.50	207.00	17.39
46	0.36618	0.4191 3	-0.0012 4	1.54E-0 6	125	367	242	267.66	285.32	15.18
38	-0.5471 4	0.2702 8	-8.47E-0 4	1.15E-0 6	121	369	248	244.92	247.84	0.06
40	-0.4732 6	0.3738 8	-0.0012 2	1.60E-0 6	148	400	252	254.49	212.98	18.32

Table 2- Table 5 lists the pressure values  $p_{2d}$  at the inflection point of the load deformation curve in the 1 pressuremeter test. Based on the calculation of bearing capacity characteristics using  $p_{2d}$  and approximate straight line method, the relative error of the two calculation methods is not more than 20%. Relative error of the layer ②-2 is 4.34%-16.11%; The relative error of the layer ②-3 is 2.34%-19.50%; Relative error of the layer ②-4 is 1.99%-16.52%; The relative error of the layer ②-5 is 0.06%-18.32%. The calculation accuracy can meet the engineering needs.

## 5. Conclusion

This article analyzes the results of the pressuremeter tests within a 46.0m range of a municipal engineering site in Nanjing. Based on the characteristics of the p-s curves on-site pressuremeter tests, and a cubic polynomial is used to fit the p-s curve with good goodness of fit; A characteristic value for determining the bearing capacity of the foundation based on the pressure value at the reverse bending point of the p-s curve was proposed. The calculation results show that the relative error of the characteristic values of the foundation bearing capacity calculated based on the pressure value at the reverse bending point of the p-s curve is within 20% compared to the bearing capacity determined by the approximate straight line method, which can meet the engineering needs.

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