Experimental investigation of bearing capacity of highway loess foundations

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Abstract: In the representative area of loess in the northwestern part of China, three typical highway foundation projects were selected to conduct experimental investigations on the bearing capacity of the subgrade soil. The three highway projects were the Can-Liu highway project in Gansu province, the Da-Yun highway project in Shanxi province, and the Yan-Yu highway project in Shanxi province. Each selected experimental site represented the properties of certain typical loess soils. According to in-situ tests (loading test, pressuremeter test and penetration test) conducted at the different test sites and related laboratory tests, the methods of determining bearing capacity for the subgrade soil in the loess area are discussed. Based on the investigation results and the property of the highway foundation engineering, this paper concludes that the bearing capacity of the subgrade soil in loess areas can be determined by pre-drilling pressuremeter tests instead of field loading tests under a restricted condition. On the other hand, the bearing capacities determined by penetration testing and laboratory testing can also be confirmed.

Résumé: Le trios ouvrages des chaussées représentatives sont choisis dans la région des parties nord-western de la Chine: L'autoroute entre Can et Liu dans la région du Gansu province, l'autoroute entre Da et Yun dans la région du Shanxi province, et l'autoroute entre Yan et Yu dans la région du Shanxi province. Le site expérimental du lœss représentative est choisis pour chaque segment de l'autoroute. Sur les résultats expérimentaux (Expriment du chargement, Expriment du chargement latéral, Expriment de la pénétration) du site et du laboratoire, les comportements mécaniques du lœss représentative sont présentes, la méthode de la détermination du capacité à supporter des chaussées différents est discutée, la conclusion est obtenue: le experiment du chargement latéral du forage remplace le teste du chargement à déterminer la capacité du lœss, et peu vérifier les paramètres obtenu par le expriment de la pénétration et du teste civile.

Keywords: Loess, bearing capacity, cone penetration tests, highways, in situ tests, laboratory studies, load tests

INTRODUCTION

With the development of northwestern part of China and construction of a national road net, more and more highway construction is to be made in the extensive areas of loess. With the effect of weathering, gulches are well developed in the loess area and many difficulties were encountered in excavation and filling (up to 70m) activities. Therefore it is important to evaluate the bearing capacity of subsoil in the area of loess.

In some organisational divisions such as architecture and water conservancy, the engineers usually estimate the bearing capacity of subsoil by means of load test, cone penetration test (CPT), dynamic penetration test (DPT), standard penetration test (SPT), or pre-drilling pressuremeter test. Among the in situ tests, the load test is a fundamental method as its results are of high accuracy. But in linear construction, it is not convenient to estimate the bearing capacity of subsoil by means of load testing. So in road engineering, it is necessary to choose a practical in situ test to allow estimation of the bearing capacity of subsoil by comparing load test to other in situ tests.

In the representative area of loess in the northwestern part of China, three typical highway foundation projects were selected to conduct experimental investigations on the bearing capacity of the subgrade soil in this paper. The three highway projects were the Can-Liu highway project in Gansu province, the Da-Yun highway project in Shanxi province, and the Yan-Yu highway project in Shanxi province. Among the three typical highway foundation projects, four test sites were selected. Four test sites were the Can-Liu test site (CL), the Da-Yun test site (DY), the Yan-Yu1 test site on the first-order terrace (YY1), and the Yan-Yu2 test site on the second-order terrace (YY2). At each test site, the evaluation of the bearing capacity of the subgrade soil was considered by means of in situ tests (load test, pre-drilling pressuremeter test, CPT, DPT and SPT) and related laboratory tests.

SUMMARY

The sketches of the four test sites are shown on figure 1~4. Different in situ tests are introduced as follows:

Load test : The loading system is made up of reaction platform, lifting jack and hand-operated oil pump press. Dial gauges (measuring range 30 – 50mm) are used to measure vertical displacement of subsoil. The loading platform is made of 40mm thick steel, whose area is elected from $0.25m^2$ or $0.50m^2$ according to the thickness of soil tested.

Cone Penetration Test (CPT) : The model of CPT machine is ZJYY-20A. The model of the data collector is JTY-3. The model of the probe is ZQD-15-3.The diameter and cross sectional area of the probe are 43.7mm and 15cm^2 separately. The effective side wall length is 70mm.

Pre-drilling pressuremeter test : The pre-drilling pressuremeter, whose model is PY-3, is used. The diameter of pressuremeter is 50mm, and the length of its measurement wall is 250mm. The model of liquid level indicator is YW-1. The load comes from high-pressure nitrogen.

Dynamic Penetration Test (DPT) : The weight of the hammer is 63.5kg. DPT is conducted with free drop method. The drop distance of the hammer is 76cm.

Standard Penetration Test (SPT) : The weight of the hammer is 63.5kg. SPT is conducted with free drop method. The drop distance of the hammer is 76cm.

Exploratory well : The soil samples excavated from exploratory well were tested promptly in the laboratory.

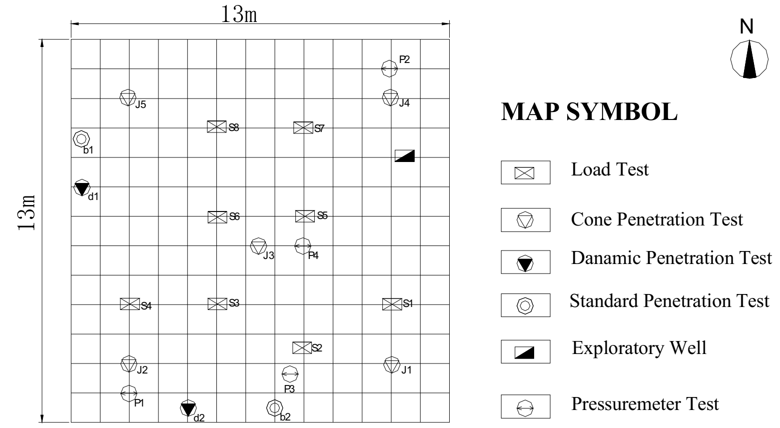

Figure1. Layout of the CL site

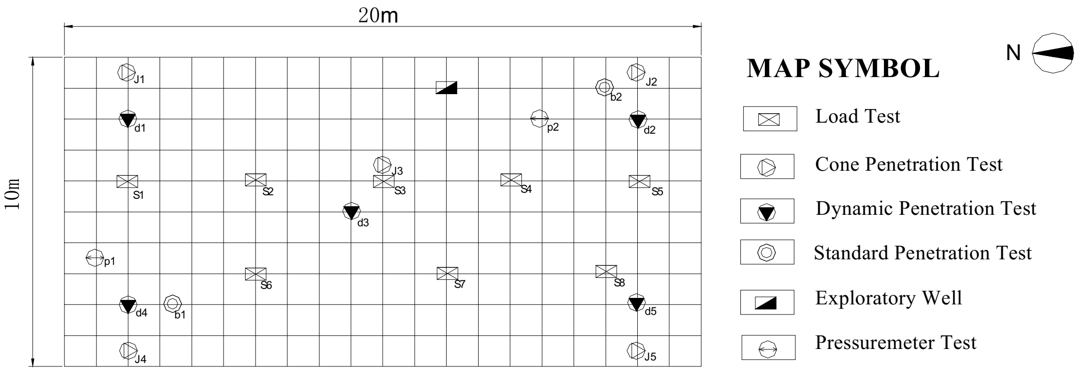

Figure 2. Layout of the DY site

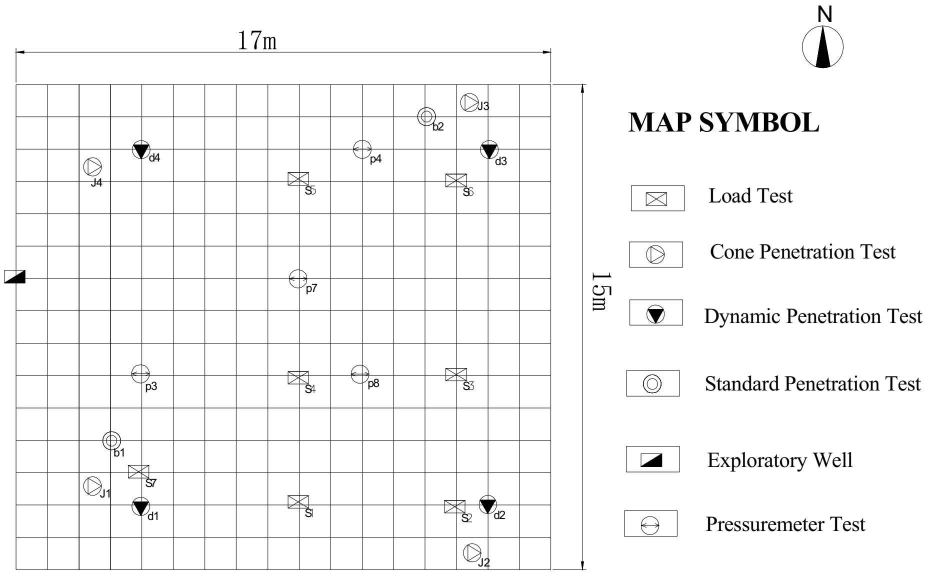

Figure 3. Layout of the YY1 site

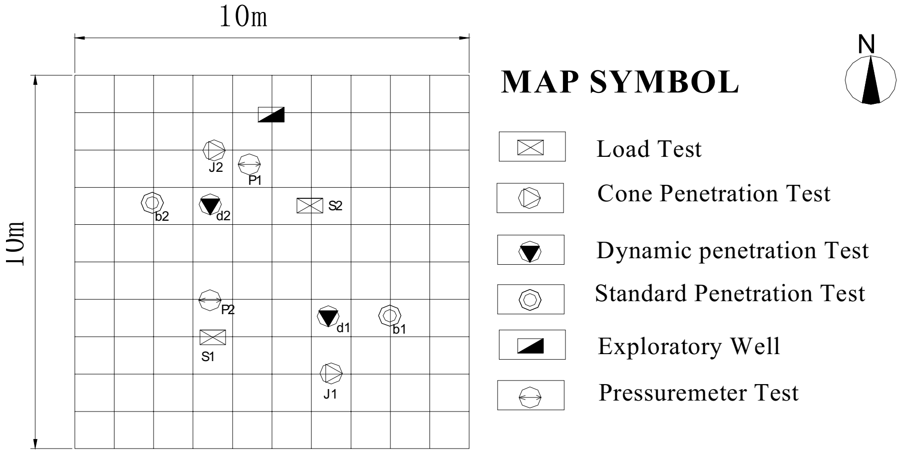

Figure 4. Layout of the YY2 site

THE RESULTS OF THE TESTS

The basic properties of soil

According to the results of CPTs and laboratory tests, the delineation of the subsoil was established in the four test sites. For the four test sites, the statistical datum for each soil layer are list in table 1~4. The first layer of subsoil is omitted from the tables as it is very thin; this layer is not discussed relevant to this article.

Table 1. Properties of subsoil for CL site

Layer No.	Description of soil	Water content (%)	Wet unit weight (kN/m^3)	Void ratio	Liquid limit	Plastic limit	Coefficient of collapsibility	Self-weight coefficient of collapsibility
②	Silt clay	20.4	14.3	1.290	31.0	20.0	0.065	0.021
③	Silt	4.5	13.3	1.144	26.7	18.0	0.103	0.051
④	Silt	7.8	14.5	1.008	27.0	17.7	0.037	0.022

Table 2. Properties of subsoil for DY site

Layer No.	Description of soil	Water content (%)	Wet unit weight (kN/m³)	Void ratio	Liquid limit	Plastic limit	Coefficient of collapsibility	Self-weight coefficient of collapsibility
②	Silt clay	12.8	14.2	1.159	27.7	17.6	0.110	0.011
③	Silt	14.0	14.2	1.180	29.0	18.8	0.073	0.006
④	silt	14.8	15.2	1.047	27.6	17.2	0.037	0.005

Table 3. Properties of subsoil for YY1 site

Layer No.	Description of soil	Water content (%)	Wet unit weight (kN/m³)	Void ratio	Liquid limit	Plastic limit	Coefficient of collapsibility	Self-weight coefficient of collapsibility
②	Silt clay	12.6	15.1	1.033	30.0	18.3	0.095	0.004
③	Silt clay	22.2	16.3	1.036	28.5	17.6	0.048	0.014
④	silt	22.9	17.5	0.903	29.3	18	0.009	0.008
⑤	Silt clay	25.7	17.8	0.914	29.9	18.3	0.005	0.003

Table 4. Properties of subsoil for YY2 site

Layer No.	Description of soil	Water content (%)	Wet unit weight (kN/m³)	Void ratio	Liquid limit	Plastic limit	Coefficient of collapsibility	Self-weight coefficient of collapsibility
②	Silt clay	7.7	14.3	1.042	28.5	17.5	0.107	0.002
③	Silt clay	9.6	14.1	1.099	26.5	16.6	0.105	0.004
④	silt	12.4	13.8	1.206	28.2	17.4	0.094	0.002

The results of in situ tests

The five in-situ tests introduced above were carried out on the four test sites: Load Test, Pressuremeter test, CPT, DPT and SPT. The load tests were carried out on the second soil layer. For the four test sites, the typical parameters for each soil layer are listed in table 5~8.

Table 5. Results of in situ tests on the CL site

Layer No.	Description of soil	Ratio penetration resistance Ps(MPa)	Dynamic penetration blows $N_{63.5}$(blows/10cm)	Standard penetration blows N(blows/30cm)	Standard vale for bearing capacity of subsoil f_k(kPa)	
					Load test	Pressuremeter test
②	Silt clay	1.2	1.5	1.5	81	82
③	Silt	3.0	3.6	5.7		228
④	Silt	4.1	6.9	12.8		233

Table 6. Results of in situ tests on the DY site

Layer No.	Description of soil	Ratio penetration resistance Ps(MPa)	Dynamic penetration blows $N_{63.5}$(blows/10cm)	Standard penetration blows N(blows/30cm)	Standard vale for bearing capacity of subsoil f_k(kPa)	
					Load test	Pressuremeter test
②	Silt clay	2.0	2.8	2.9	130	140
③	Silt	3.3	4.4	6.4		201
④	Silt	3.4	5.1	10.6		278

Table 7. Results of in situ tests on the YY1 site

Layer No.	Description of soil	Ratio penetration resistance Ps(MPa)	Dynamic penetration blows $N_{63.5}$(blows/10cm)	Standard penetration blows N(blows/30cm)	Standard vale for bearing capacity of subsoil f_k(kPa)	
					Load test	Pressuremeter test
②	Silt clay	4.1	4.9	9.2	209	200
③	Silt clay	3.0	3.7	8.7		200
④	Silt	4.2	7.5	10.6		261
⑤	Silt clay	8.5	10.3	19.2		295

Table 8. Results of in situ tests on the YY2 site

Layer No.	Description of soil	Ratio penetration resistance Ps(MPa)	Dynamic penetration blows $N_{63.5}$(blows/10cm)	Standard penetration blows N(blows/30cm)	Standard vale for bearing capacity of subsoil f_k(kPa)	
					Load test	Pressuremeter test
②	Silt clay	7.3	9.1	14.5	300	296
③	Silt clay	4.7	4.9	8.3		242
④	Silt	3.6	3.9	7.6		207
⑤	Silt clay	4.7	5.8	13.1		238

ANALYSIS ON THE DIFFERENT METHODS OF EVALUATING BEARING CAPACITY OF SUBSOIL

Comparative analysis on the bearing capacity of subsoil by load tests and the pressuremeter tests

Twenty-five load tests were carried out on the four test sites on the second layer (② silt clay). The eighty pressuremeter tests were put up in eight bored holes at the four test sites. On each test site, the results of the pressuremeter tests were obtained within different strata and the results have been analysed and are presented in table 9. Because the load test is the most direct and reliable measurement of bearing capacity, the bearing capacity of subsoil obtained by other test methods is contrasted to that obtained from load tests in order to assess the applicability of the other methods. In order to validate the accuracy of the bearing capacity obtained by the other methods, we take the results obtained by the load tests as the standard, and contrast this against the results obtained by the other methods. We calculate the relative error as follows:

$$\varepsilon = \frac{f_{kl} - f_{ko}}{f_{kl}} \times 100 \quad (1)$$

where: ε is the relative error in %;

f_{kl} is the standard value of the bearing capacity of the subsoil, which is determinate by the load tests, kPa;

f_{ko} is the standard value of the bearing capacity of the subsoil obtained by other methods (the pressuremeter test, the penetration test, the experiential formulae or the experiential charts etc.), kPa.

From table 9, we find that the standard value of the bearing capacity of the subsoil obtained by the pressuremeter tests on the four test sites have a relative error ranging from -7.7% to 4.3%. Taking a range of relative error between -15.0% to 15.0% as an acceptable criterion, these four test sites would be seen to satisfy this requirement. So, the measurement of bearing capacity of the subsoil by the pressuremeter test method approaches to the standard value obtained from the load tests in the shallow part of the subsoil, and satisfies the precision requirement. So, in the shallow of the subsoil, we could complement the load tests with pressuremeter tests, or substitute the load test to some extent in ascertaining the bearing capacity of the subsoil in the road engineering in loess soil area.

Comparative analysis on the bearing capacity of subsoil by penetration tests and laboratory tests with the load tests

Among the tests uses to evaluate bearing capacity, the load test is the most effective and accurate. But it is restricted by a series of practical factors causes, such as the experimental equipment is too ponderous, it is not carried portable, and the test occupies too much time and money. So engineers try to find other more convenient and simple method to measure the bearing capacity of subsoil in geotechnical practice. Geotechnical engineers usually adopt the penetration tests (CPT, DPT and SPT) and laboratory tests to obtain the bearing capacity of subsoil. Now also there are many experiential formulae and empirical design charts established to determinate the bearing capacity of subsoil.

According to the testing results shown on table 1 to table 8, we could determine the bearing capacity of the second layer soil (② silt clay on each test site) by the formulae and empirical charts from relevant design manuals or Codes. These can also be contrasted with the results obtained by load tests. The comparisons are shown in table 10 to table 13.

Table 9. Comparison of the bearing capacity by pressuremeter tests with load tests

Test site	Water content (%)	Wet unit weight (kN/m^3)	Void ratio	Liquid limit	Plastic limit	Test method	Standard vale for bearing capacity of subsoil f_k(kPa)	Relative error ε (%)
CL	20.4	14.3	1.290	31.0	20.0	Pressuremeter test	82	-1.2
						Load test	81	
DY	12.8	14.2	1.159	27.7	17.6	Pressuremeter test	140	-7.7
						Load test	130	
YY1	12.6	15.1	1.033	30.0	18.3	Pressuremeter test	200	4.3
						Load test	209	
YY2	7.7	14.3	1.042	28.5	17.5	Pressuremeter test	296	1.3
						Load test	300	

Table 10 Comparison of the bearing capacity from CPT with load tests Note:*- Figures from the Engineering Geology Manual

Test site	Ratio penetration resistance Ps (MPa)	Standard vale for bearing capacity of subsoil fk(kPa)						
		Load test	fk=87.8Ps+24.36 (Table 3-3-5)*	ε(%)	fk=80Ps+31.8 (Table 3-3-5)*	ε(%)	Table 3-3-7*	(%)
CL	1.2	81	130	-60.5	128	-58.0	105	-29.6
DY	2.0	130	200	-53.8	192	-47.7	140	-7.7
YY1	4.1	209	383	-83.3	360	-72.2	219	-1.05
YY2	7.3	300	665	-121.7	616	-105.3	267	11.0

Table 11 Comparison of the bearing capacity by DPT with load tests

Test site	Dynamic penetration blows $N_{63.5}$(blows/10cm)	Standard vale for bearing capacity of subsoil f_k(kPa)		
		Load test	Table 3-2-20*	ε(%)
CL	1.5	81	90	-11.1
DY	2.8	130	144	-10.8
YY1	4.9	209	207	1.0
YY2	9.1	300	323	-7.7

Note: *- Figures from the Engineering Geology Manual.

In table 10 to table 13, the precision of the bearing capacity results obtained by penetration tests and laboratory tests through adopting the design formulae and charts, were appraised by the relative error in comparison with the results of the load test. As before we can take a relative error of between -15.0%~15.0% as satisfying the accuracy requirement.

According to the results of CPTs on four test sites: the relative error of the standard bearing capacity of the subsoil, is calculated from design manual formulae (Engineering Geology Manual, table 3-3-5) and is found to provide errors of -121.7%~47.7%. So, the four test sites fail to satisfy the accuracy requirement. Alternatively, the relative error of the bearing capacity of the subsoil (Engineering Geology Manual, table 3-3-7) is between -29.6%~11.0%, and so the CL site, the YY1 site and YY2 site satisfy the accuracy requirement, but the DY site could not satisfy the accuracy requirement.

Table 12 Comparison of the bearing capacity by SPT with load tests

Test site	Standard penetration blows N(blows/30cm)	Standard vale for bearing capacity of subsoil f_k(kPa)		
		Load test	**Table 3-2-37***	**ε(%)**
CL	1.5	81	35	56.8
DY	2.9	130	68	47.7
YY1	9.2	209	214	-2.4
YY2	14.5	300	338	-12.7

Note: *- Figures from the Engineering Geology Manual.

Table 13 Comparison of the bearing capacity by geotechnical parameters with load tests

Test site	Water content (%)	Void ratio	Liquid limit	Plastic limit	Standard vale for bearing capacity of subsoil fk(kPa)				
					Load test	**Add table 10.1†**	**ε (%)**	**Table D.0.1-9‡**	**ε (%)**
CL	20.4	1.290	31.0	20.0	81	148	-82.7	131	-61.7
DY	12.8	1.159	27.7	17.6	130	165	-26.9	175	-34.6
YY1	12.6	1.033	30.0	18.3	209	182	12.9	216	-3.3
YY2	7.7	1.043	28.5	17.5	300	178	40.7	260	13.3

Note: †-Figures from the Building Code for Wet-pouch Loess Area (GBJ25-90).
‡ - Figures from the Code for Geology Investigation of Railway Engineering (TB10012-2001 J124-2001).

According to the results of DPTs on four test sites, the relative error of the standard bearing capacity of the subsoil, is calculated (Engineering Geology Manual, table 3-2-20) is between -11.1%~1.0%. So the four test sites satisfy the accuracy requirement.

According to the results of SPTs on four test sites: the relative error of the standard bearing capacity of the subsoil, is calculated (Engineering Geology Manual, table 3-2-27) is between -12.7%~56.8%. So the YY1 site and the YY2 site could satisfy the accuracy requirement, but the CL site and the DY site could not satisfy the accuracy requirement.

According to the results of laboratory tests on four test sites: the relatively error of the standard bearing capacity of the subsoil is calculated (Building Code for Wet-pouch Loess Area (GBJ25-90), Add table 10.1) is between -82.7%~40.7%. So the YY1 site could satisfy the requirement, but the CL site, the DY site and the YY2 site could not satisfy the requirement. The relative error of the bearing capacity of the subsoil, is calculated (Code for Geology Investigation of Railway Engineering (TB10012-2001 J124-2001), table D.0.1-9) is between -61.7%~13.3%. So the YY1 site and YY2 site could satisfy the accuracy requirement, but the CL site and the DY site could not satisfy the accuracy requirement.

By analysis as above, we find that the accuracy of confirming bearing capacity of the subsoil with in-situ tests and laboratory tests is not consistent. Because there are large expansion of territory and many kinds of soil in China, the geotechnical engineers need guidance based on regional as well as personal experience when choosing the method of assessment. Sometimes, it is necessary to carry out validation of empirical formulae and design charts by load test or other effective methods.

Discussion on ascertaining the bearing capacity of deep soil layer by pressuremeter test

The deep layer flat load test and the spiral slab load test are effective methods to ascertaining the bearing capacity of deep soil layers. In general, the deep flat load test is suitable for soil layer more than 3m depth and above the water table, while the spiral slab load test is suitable for deep soil layers below the water table. But, these two tests take a long time and have a high cost. So, the geotechnical engineers would again seek more convenient methods to ascertain the bearing capacity of deep soil layers. As reviewed above, the load test can be replaced by the pressuremeter test when soil layer is shallow below the earth surface in some situations. But, it is not certain whether this can be done when the soil layer is at greater depth.

The bearing capacity of the deep layer (soil layer of ③, ④ and ⑤) obtained from pressuremeter tests and penetration tests (CPTs, DPTs, and SPTs) are compared in figure 5~7. There are no regular relationships between the bearing capacity from pressuremeter tests from penetration tests. So, further study needs to be carried out to determine whether pressuremeter test may replace the deep load test or not.

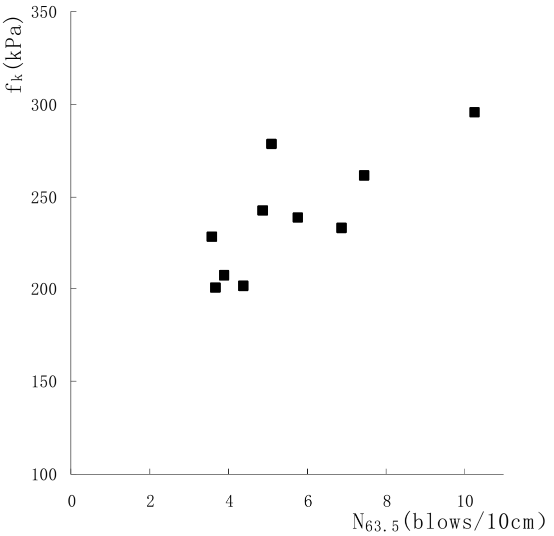

Figure 5. Relationship between the bearing capacity of deep soil layer (f_k) and DPT ($N_{63.5}$)

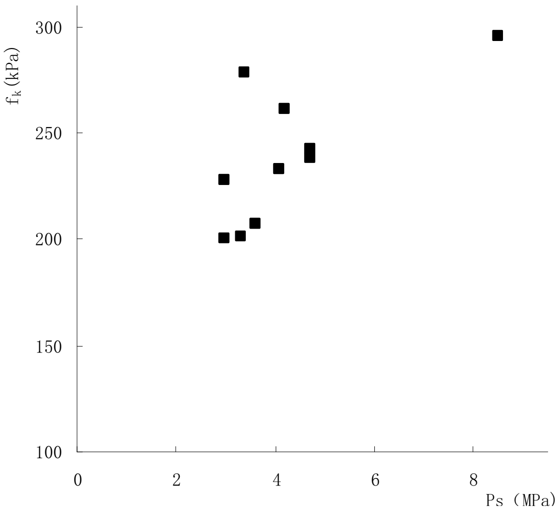

Figure 6. Relationship between the bearing capacity of deep soil layer (f_k) and CPT (Ps)

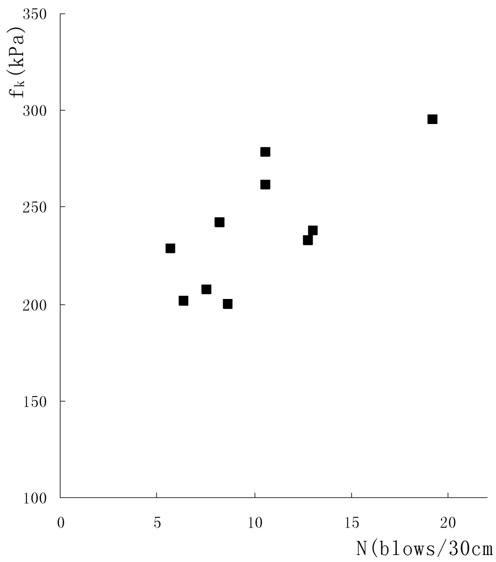

Figure 7. Relationship between the bearing capacity of deep soil layer (f_k) and SPT (N)

CONCLUSION

We have discussed a range of methods to ascertain the bearing capacity of the subsoil in road engineering through the in-situ tests (load tests, pressurementer tests, CPTs, DPTs and SPTs) and laboratory tests on four test sites in loess, and some valuable results have been obtained.

The load test is the most directly and reliable method of confirming the bearing capacity of the subsoil, we must do the load test to confirm the bearing capacity of the subsoil in the large-scale projects (e.g. viaduct and large-scale bridges etc.) and commonly projects in the area without construction experience.

To the less important projects and where previous construction experience is available, the pressuremeter test could substitute the load test at the shallow part of the ground surface. At the deeper part of the ground, the reliability of the pressuremeter test to replace the load test needs further research.

Geotechnical engineers have accumulated abundant experience in assessing the bearing capacity of the subsoil by the penetration tests (CPTs, DPTs and SPTs) and laboratory tests. This experience is presented in the correlation criteria or in the form of empirical formulae and charts. In China because there is a large territory and many kinds of soils, and the formulae or charts were derived in some special area, the geotechnical engineers need more regional experience and guidance when choosing the appropriate assessment method. Sometimes, it is necessary to carry out specific validation and correlation work, based on the load test or other effective in –situ methods.

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