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Determination and Evaluation of Strength Characteristics of Dry Jet Mixing

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Abstract: Dry jet mixing (DJM) for soft soil stabilization has been widely used since 1980s. The quality and strength of stabilized columns are fundamental parameters to evaluate the stabilization work. This paper presents the standard penetration test (SPT) method and its test results on cement columns. It is shown that SPT is an effective and simple method for inspecting and evaluating cement columns. The strength characteristics along the length of the column, a good correction between SPT blow count and the unconfined compressive strength are achieved.

Key words: dry jet mixing, cement columns, SPT, unconfined compressive strength

DJM is a soil improvement technology which pneumatically delivers powdered reagent into ground and mixes it with in-situ soils to form a soil-reagent column. The chemical reactions between soils and dry reagents such as cement power or lime increase the strength and reduce the compressibility of the very soft ground. Due to its many advantages, DJM has obtained increasing attention compared to other methods since it was developed by Sweden engineer Kjeld Paus in 1967. Since the 1980s, it has been a large increase in the use of DJM both in Nordic countries and Japan. Today the method is used world-wide in Europe, USA and Asia[1].

The deep mixing method was introduced into China in 1980 from Japan. In 1983, the first DJM equipment was developed by Wuhan Research Institute of Engineering Machinery of China and successfully tested in soft soil improvement for railway engineering. Although there were some undesirable practices in building engineering during 1980s, DJM has been spread rapidly all over the China since 1990s, especially in road and railway embankments. The typical parameters for DJM with equipment producing stabilized soil cement columns in China are:

The binder material: cement, lime + cement (occasionally);

Content of binder material: 10% – 15% soil weight;

The column diameter: normally 500 – 600 mm;

Maximum depth: 15 m;

Typical area radios: 0.1 – 0.25;

Plan arrangement of columns: triangular;

Installation: mixing 1 – 3 times.

DJM are most frequently used to reduce settlements and increase the stability or both, many theoretical and empirical methods for calculating settlements and analyzing the stability were developed during the last decade[2,3]. Although parameters of cement columns such as modulus, strength can be measured by laboratory tests, it seems to be much more difficult to determine the parameters accurately as a result of the big difference between the laboratory and the field performances. In Sweden and Finland, a mechanical column penetrometer was developed in 1980s[4]. The van penetrometer, cone penetration test (CPT) and other in-situ tests are finding their practice in cement columns. However, the available methods are not sufficient to evaluate the cement column stabilized works[5].

In this paper the standard penetration test (SPT) on cement columns for determining the strength and inspecting the quality is conducted. The strength characteristics along cement columns are investigated. The relationship between SPT blow count and unconfined compressive strength and its engineering application are discussed.

1 The Strength Changes Along the Length of the Cement Column

The shear strength or unconfined compressive strength of the cement column is a function of many factors such as soil properties, binder content, construction technology and environment(such as temperature, etc). In order to investigate the stabilized soil characteristics, the SPT was made on different designed cement columns in Lianyungang section of Lianhuo freeway in China. The cement column length changes from 8 m to 13 m with the diameter 500 mm corresponding to the soft clay

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thickness, whereas the amount of the cement used from 55 – 75 kg/m for different water contents. Because the core of approximately 100 mm of the cement column performs less representative across the diameter, the SPT was implemented at the location of the 2/5 radius from the center. Disturbed samples from the penetration probe have been visually inspected for cement contents and mixing uniformity. Moreover, undisturbed core samples were consequently taken every 1.5 m along the columns with normal core sample equipment just above the SPT testing level. It can be recognized that each unconfined compressive strength q_u obtained from the core sample at laboratory corresponds to a SPT blow count N approximately at the same position.

Fig.1 and Fig.2 show respectively SPT blow counts and the unconfined compressive strength along

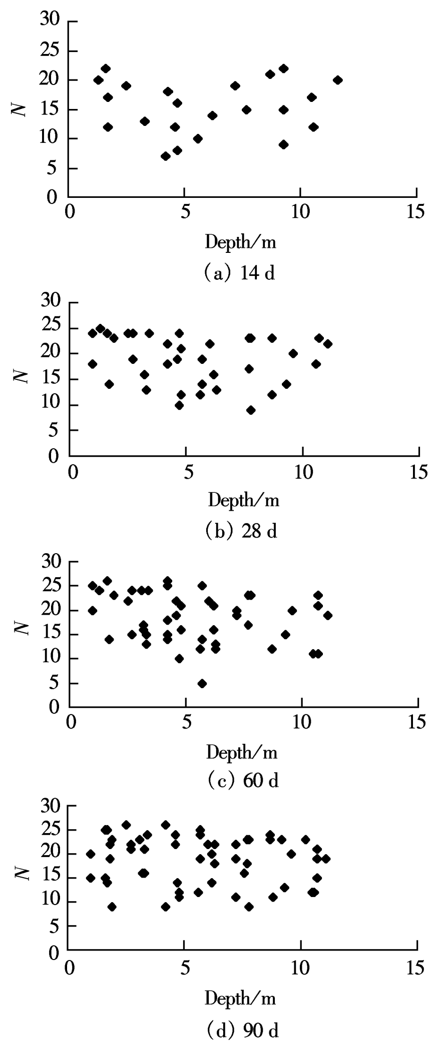


Fig. 1 Variation of SPT blow count with depth

cement columns at different ages. It is obvious that the strength or the modulus of cement columns is generally uniform, although the strength increases with the time. This performance is conformed with the test results in Norway[6].

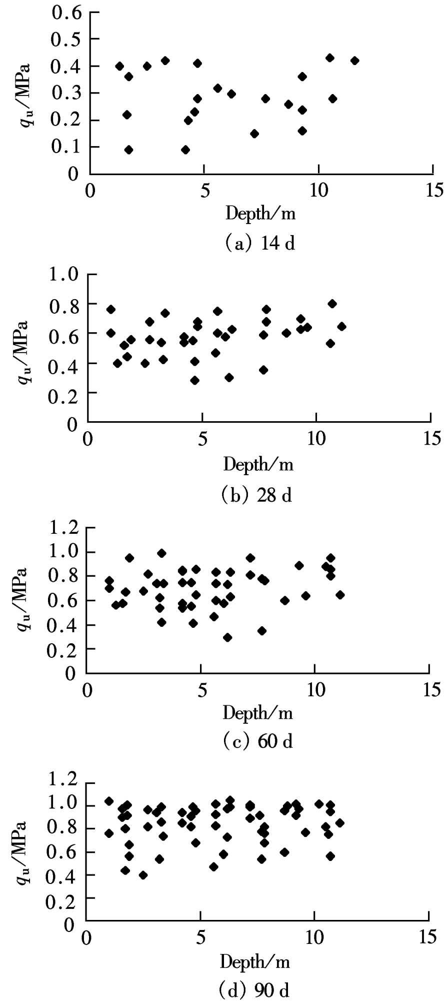


Fig. 2 Variation of compressive strength with depth

2 Relationship between N and q_u

The relationship between the SPT blow count N and the unconfined compressive strength q_u is presented in Fig.3 and empirical equations are given as follows:

$$q_u = 6.8N + 19.8 \quad (7\text{ d}) \qquad (1a)$$

$$q_u = 8N + 150.3 \quad (14\text{ d}) \qquad (1b)$$

$$q_u = 10.5N + 268.5 \quad (28\text{ d}) \qquad (1c)$$

$$q_u = 8.3N + 364.4 \quad (60\text{ d}) \qquad (1d)$$

$$q_u = 6N + 446.3 \quad (90\text{ d}) \qquad (1e)$$

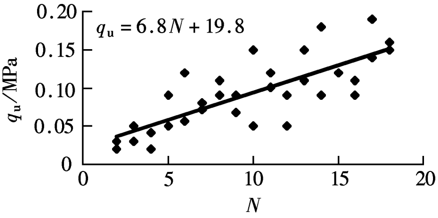
It is noticed from Fig.3 that the SPT blow count increases linearly with the unconfined compressive strength, furthermore, the lines with different ages are almost parallel(see Fig.4). On the other hand, the strength develops with time in Fig.4 can be described by the expression(see Fig.5):

$$q_u = 160 \ln T - 240 \qquad (2)$$

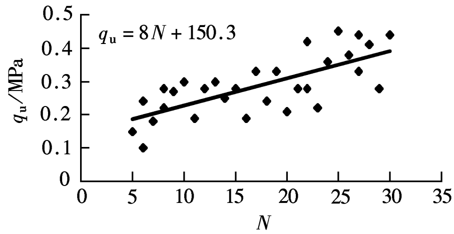
Hence, the relationship can be summarized as

$$q_u = 8N + 160 \ln T - 240 \qquad (3)$$

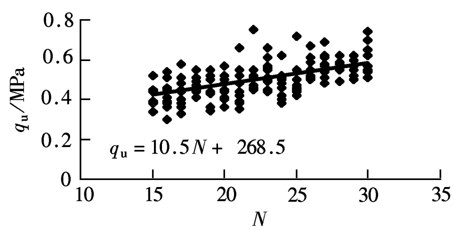
where q_u(kPa) is the unconfined compressive strength



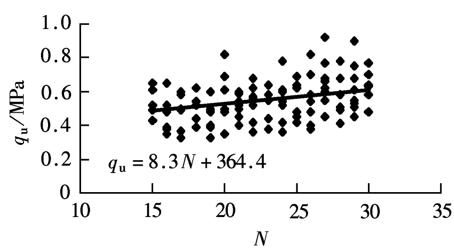
(a) 7 d



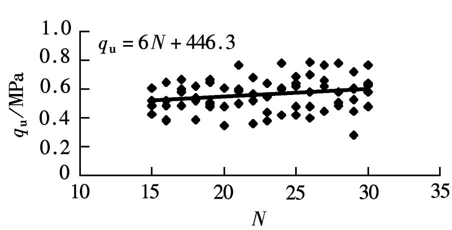
(b) 14 d



(c) 28 d



(d) 60 d



(e) 90 d

Fig.3 Relationship between N and q_u

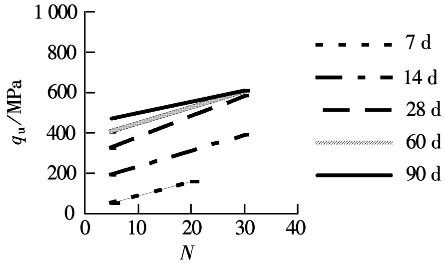


Fig.4 Comparison of relationships between N and q_u

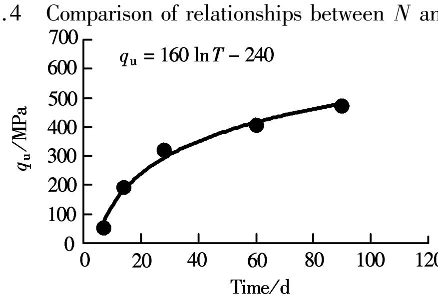


Fig.5 Variation of compressive strength with time

of the core sample at the time T; N is SPT blow count modified from rod length at the time T; T (d) is the time after the cement column installation.

In engineering practice, test columns are often installed before commencing the actual stabilization work. With the economic and simple SPT, Eq. (3) is very effective for finding the right design parameters such as the strength, binder amounts.

3 Engineering Application

The bearing capacity of the cement column improved ground depends on contributions of both the column and the surrounding unstabilized soils. It can be calculated by the weighted average of the column and the soil bearing capacity as follows:

$$\sigma_{sp} = \alpha\sigma_p + (1 - \alpha)\sigma_s \tag{4}$$

where σ_{sp} is the bearing capacity of the composite ground(kPa); σ_p is the bearing capacity of the cement column(kPa); σ_s is the bearing capacity of the unstabilized soils(kPa); α is the area ratio of the column area and the stabilized area.

The bearing capacity of the cement column σ_p can be easily evaluated from the SPT results by the following:

$$\sigma_p = k(8N + 160 \ln T - 240) \tag{5}$$

where k is the index of disturbance which equals to the ratio of undisturbed strength and disturbed strength.

The undisturbed strength can be obtained from the laboratory with the cement soil mixing sample, while the compressive strength of the core sample from the SPT boring is the disturbed strength because of the boring and testing disturbance. In most cases, $k = 2.5$[7].

Considering the uniform performance along the cement column, the average SPT blow count can be taken as the N for above equation.

Tab.1 shows the comparison of bearing capacities of single columns determined by SPT and state load tests (SLT), where the SPT was made after the SLT at the same column. There is a desirable consistent results with two methods. In other words, Eq. (3) is effective in engineering practice.

For stability analysis of embankments or slopes, the global shear resistance τ_{sp} corresponds to the weighted average shear strength of columns and unstabilized soils

Tab.1 Comparison of bearing capacity determined with SPT and SLT

Column number	Age after installation/d	Column length/m	Column diameter/mm	Average N	Bearing capacity/kN		
					SPT	SLT	Error/%
16 – 13	63	13	500	13.0	258	240	7
10 – 11	45	12	500	16.4	245	270	9
11 – 19	67	13	500	15.0	262	270	3
13 – 9	46	13	500	14.0	237	240	1

$$\tau_{sp} = \alpha\tau_p + (1-\alpha)\tau_s \qquad (6)$$

where τ_p is the shear strength of the cement column; τ_s is the shear strength of the unstabilized soils.

Because the permeability of the cement column is very low, the undrained shear strength can be used for the stability analysis[2,3]. Therefore,

$$\tau_p = 0.5q_u \qquad (7)$$

where q_u can be obtained from Eq.(3) times the index of disturbance k with the average SPT blow count.

For settlement estimation of cement columns composite ground, Eq.(3) is also found its effective to determine the modulus of the column with the relationship between the modulus and the unconfined compressive strength or SPT blow count.

4 Conclusions

A large number of field SPT tests and laboratory unconfined compressive tests have been implemented on cement columns formed by dry jet mixing for soft ground improvement. The strength characteristics along the length of cement column and determination methods are studied. The following points may be summarized in conclusion.

1) The SPT is an economic and effective method to ensure the strength and quality of stabilized columns. The SPT is highly recommended as the quality control method for DJM;

2) The strength parameters along the cement column are generally homogeneous with the increase logarithmically with time;

3) There is a unique relationship between the SPT blow count N and the unconfined compressive strength q_u of the cement column at a certain time;

4) The SPT oriented results can meet engineering practical needs for determining the bearig capacity, the shear resistance and modulus in stability analysis and settlement estimation of DJM composite ground.

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粉喷桩强度特性的确定与评价

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摘　要　自从20世纪80年代以来,粉喷桩在软土地基处理中得到了广泛的应用.加固体的质量和强度是评价粉喷桩加固效果的主要参数.本文提出了标准贯入试验检测方法,并给出了粉喷桩的测试结果,研究表明标准贯入试验是一种简单而有效的粉喷桩检测和评价方法.得到了沿桩长方向的强度特性及标准贯入试验击数和无侧限抗压强度之间有着良好的对应关系.

关键词　粉喷桩,水泥桩,标准贯入试验,无侧限抗压强度

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