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Technical Note

Bearing capacity of unsaturated expansive soils

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Abstract. It is difficult to determine the bearing capacity of a foundation in unsaturated expansive soil, although this is most important. The bearing capacity of unsaturated expansive soil is related to the drying and wetting environment. Swelling pressure occurs when the soil volume change is constrained as an expansive soil is inundated. The expansive lateral pressure, induced by the swelling pressure is similar to the passive earth pressure. By considering the effect of the expansive lateral pressure in Terzaghi's bearing capacity formula, the bearing capacity of unsaturated expansive soil is derived. Because it is very difficult to measure suction *in situ*, the bearing capacity is expressed using the expansive lateral pressure offers a feasible approach to calculate the bearing capacity of a foundation in unsaturated expansive soil, when suction is not measured. Plate load tests to measure the bearing capacity in situ were performed for the foundation in natural soil and saturated soil immersed by water. The verification of the bearing capacity formulae presented in this paper is conducted by comparing the predicted results with the results of the plate load tests on unsaturated expansive soils in Handan and Ningxia, China.

Key words. bearing capacity, expansive soil, plate load test, swelling pressure, unsaturated soil

1. Introduction

Expansive soil is a natural, highly dispersed and plastic soil, which contains mainly clay minerals and is very sensitive to either drying or wetting. Clay particles of expansive soil have large specific surface area and electrical forces acting on the surface of the particles are more influential than the gravitational forces. Montmorillonite is the most expansive type of clay mineral and its structural formula is $Al_4Si_8O_{20}(OH)_4n(H_2O)$. The exchange capacity of montmorillonite mineral is $80 \sim 150$ meq per 100 gm (Li et al., 1992). Expansive soil is widely distributed in the globe and is found in more than 40 countries and regions. China is one of the countries with a large distribution of expansive soil, which has been discovered in more than 20 of its provinces and regions. In China, expansive soil is mainly lacustrine, residual, slopewash, alluvial and diluvial in origin (Xu and Liu, 1999).

Studies of the mechanical and engineering behaviors of expansive soil have been emphasized all over the world because of their wide distribution and serious harm. Expansive soil is called the 'hidden hazard' and it was reported that the economic losses caused by expansive soil amount to $2.3 billion per year in 1973, far more than that from the total losses caused by floods, earthquakes and windstorms put together in U.S.A. (Jones and Holtz, 1973; Chen, 1988). In Japan expansive soil is called ‘problem soil’, for it often brings about foundation deformation and mud pumping of many roadbeds, the heaving of tunnel arches and landslides in embankments, etc. It is said that ‘there is no cut that would not cause slides’ and ‘there is no embankment that would not collapse’ in regions of expansive soil in China (Survey Institute of Administration Committee of Yangtze River Water Conservancy, 1982).

The study of bearing capacity has taken more than 50 years (Terzaghi, 1943; Meyerhof, 1951; Vesic, 1975), and many results have been published for bearing capacity recently (Griffiths, 1982; Bolton and Lau, 1993). Expansive soil is one type of unsaturated soil. Many important results on the mechanics of expansive soils are obtained by using unsaturated soil mechanics. Fredlund and Rahardjo (1993) have studied the bearing capacity of unsaturated soil by considering the shear strength caused by suction as cohesion in Terzaghi’s formula. Xu and Fu (2000) have discussed the bearing capacity of the foundation in unsaturated expansive soil by considering the influence of swelling pressure.

In this paper, the characteristics of bearing capacity of unsaturated expansive soil are analyzed. It is assumed that the expansive soils in their natural state are unsaturated. It is also assume that the soils approach a saturated state after immersing. A method to determine the bearing capacity is presented for the foundation in unsaturated expansive soil by using the expansive lateral pressure. The method proposed to calculate the bearing capacity is verified by the results of plate load tests performed *in situ* on Handan and Ningxia expansive soils.

2. Characteristics of bearing capacity of expansive soil

The study on the bearing capacity of unsaturated expansive soil has been performed through field tests (Zhai et al., 1988; Wang, 1995; Xu and Fu, 2000). It was found that the bearing capacity of expansive soil varied with water content and expansion potential. The characteristics of bearing capacity of unsaturated expansive soil are summarized as follows.

2.1. INFLUENCE OF WATER CONTENT

Unlike the bearing capacity of saturated soil, the bearing capacity of unsaturated expansive soil is not a constant and it varies with water content. Since the shear strength of unsaturated soil is divided into two parts, the bearing capacity of unsaturated expansive soil also contains two parts. One is the bearing capacity of the saturated soil, and another is the bearing capacity caused by the suction. Letting q_u denote the bearing capacity of unsaturated expansive soil, and $(q_u)_{\text{sat}}$ indicate the bearing capacity of saturated soil, the relationship between q_u and $(q_u)_{\text{sat}}$ is written as follows:

$$q_u = (q_u)_{\text{sat}} + q_s \tag{1}$$

where q_s is the increase in ultimate bearing capacity caused by the suction.

The bearing capacity caused by the suction of unsaturated expansive soils, q_s increases with suction. With increase of water content, the suction of unsaturated soil decreases and q_s also decreases. The relationship between q_s and the suction of unsaturated expansive soil is described by the following formula (Fredlund and Rahardjo, 1993),

$$q_s = c_s N_c \tag{2}$$

where N_c is the bearing capacity factor in Terzaghi's formula and c_s is the suction cohesion, which is caused by suction. The suction cohesion is defined as (Fredlund and Rahardjo, 1993),

$$c_s = u_s \tan \phi^b \tag{3}$$

where u_s is the matric suction, $u_s = u_a - u_w$, u_a and u_w are the pore-air pressure and the pore-water pressure, respectively, ϕ^b is the angle indicating the rate of increase in shear strength relative to matric suction.

For unsaturated expansive soil, the suction cohesion after shows a power law relationship with water content (as will be shown later). This can be expressed as:

$$c_s = aw^n \tag{4}$$

where a and n are statistical constants and w is the gravimetric water content (%).

Combining Equation (2) with Equation (4), the relationship between q_s and the water content of unsaturated expansive soils is given as

$$q_s = aN_c w^n \tag{5}$$

This relationship will be investigated later in the paper.

2.2. VARIATION WITH SWELLING PRESSURE

Swelling pressure, as measured in the laboratory is the maximum axial pressure which is needed to keep constant volume of a laterally restrained specimen. There are many methods to use to measure the swelling pressure of expansive soil. The constant volume method is the most common method. After the specimen is settled in the oedometer, water is supplied. Swelling of the specimen is controlled by the addition of further loads. The aim is to arrive at a load at which there is neither swelling nor compression, maintaining the specimen at the original volume.

Lu (1992) suggested a linear relationship between swelling pressure and the suction cohesion of unsaturated expansive soils, i.e.

$$c_s = mp_s \tag{6}$$

where p_s is the swelling pressure, m is a statistical constant and is usually less than 1.0 Substituting Equation (6) into Equation (2), gives into the following

$$q_s = N_c mp_s \tag{7}$$

Equation (7) gives the relationship between q_s and the swelling pressure of unsaturated expansive soils. It suggests the relationship will be linear of the form:

$$q_s = kp_s \tag{8}$$

This will be explored later in the paper.

3. Effect of swelling pressure on bearing capacity

The bearing capacity of an unsaturated soil is obtained by using total cohesion instead of the undrained cohesion of saturated soils in Terzaghi's formula (Fredlund and Rahardjo, 1993), i.e.

$$q_u = s_c c N_c + s_q q N_q + s_\gamma \frac{1}{2} \gamma B N_\gamma \tag{9}$$

where c is the total cohesion, whose value equals the sum of suction cohesion (c_s) and the undrained cohesion of saturated soil (c_o), q is the surcharge, B is the width of footing, γ is the unit weight, N_c, N_q and N_γ are the bearing capacity factors, whose values depend only on the angle of friction, s_c, s_q and s_γ are the shape factors. Usually $s_c = 1 + B/L$, $s_q = 1.0$ and $s_\gamma = 1.0$, where L is the length of footing, and for a square footing, $s_c = 1.2$, and $s_c = 1.0$ for a strip footing. It is well known that the angle of friction is a constant for non-swelling unsaturated soils with different matric suctions (Escario and Saez, 1986). Therefore, the bearing capcity factors N_c, N_q and N_γ are taken to be equal to those of a saturated soil.

Matric suction and the angle ϕ^b, which provide the suction cohesion, are very difficult to measure accurately. Another variable is needed to replace the matric suction to express the bearing capacity. Swelling pressure is a special mechanical parameter for expansive soils and is related to the water content, like the matric suction. In addition, swelling pressure is easier to measure than matric suction. Therefore, swelling pressure is a practical replacement for matric suction.

Katti (1987) has compared the passive earth pressure distribution in sand, cohesive soil and black cotton (expansive soil) (Figure 1). It can be seen that the earth pressure of expansive soil is larger than that of sand and cohesive soil. The expansive lateral pressure measured is in proportion to swelling pressure and is expressed as follows (Katti, 1987):

$$p = \frac{p_s \dfrac{z}{z_0}}{a + 0.6 \dfrac{z}{z_0}} \tag{10}$$

where p is the distribution of expansive lateral pressure, which is caused by swelling pressure, p_s is the swelling pressure, a is the percent of clay, z is the depth, z_0 is the unit of depth, $z_0 = 1$ cm.

It must be noted that Katti's results are for a saturated expansive soil, and may not be valid for an unsaturated soil.

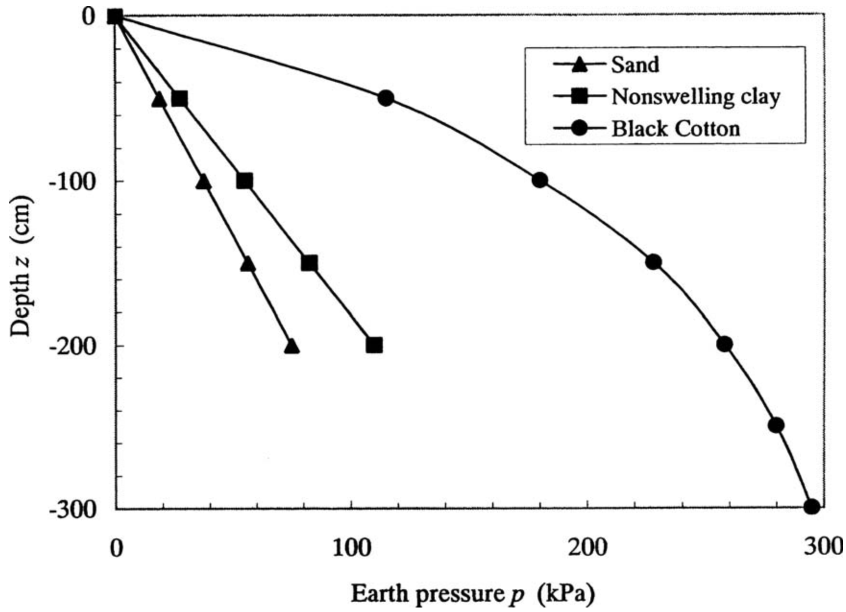

Figure 1 Earth pressure distribution profiles of three soils (After Katti, 1987)

In the limit equilibrium analysis of general bearing capacity failure, an assumption is made that the direction of the expansive lateral pressure is perpendicular to the side of an elastic wedge (Figure 2b). From the force equilibrium of the elastic wedge (Figure 2c), the ultimate load of the foundation in unsaturated expansive soils can be written as follows:

$$Q_u = 2P_p \cos(\psi - \phi) + cB \tan\psi - \frac{1}{4}\gamma B^2 \tan\psi + 2P_{ps} \cos\psi \tag{11}$$

where Q_u is the ultimate load, P_p is the passive earth pressure, B is the width of footing, c and ϕ are the cohesion and angle of friction, respectively, ψ is the angle between the elastic wedge side and horizontal plane (see Figure 2c) and is assumed equal to $45^\circ + \phi/2$ as in most bearing capacity analysis, γ is the unit weight, P_{ps} is the expansive earth force arising from the expansive lateral pressure along the elastic wedge.

If the distribution of expansive lateral pressure is given in Equation (10), the total amount of expansive lateral pressure acting on the elastic wedge side can be calculated by integrating Equation (10). It should be noted that Katti (1987) indicates that the observed passive resistance is much smaller than the passive resistance obtained by integrating the pressure distribution diagram. This can be attributed to the drastic reduction in shear strength near the surface as a result of swelling. Therefore, integrating Equation (10) is likely to give an estimate of the lateral pressure. Nevertheless, it is given:

$$P_{ps} = \int_0^{B/2\cos\psi} p\left[\mathrm{d}\left(\frac{z}{z_0}\right)\right] = \frac{5p_s B}{6\cos\psi} - \frac{25}{9} p_s a \ln\left(1 + \frac{3B}{10a\cos\psi}\right) \tag{12}$$

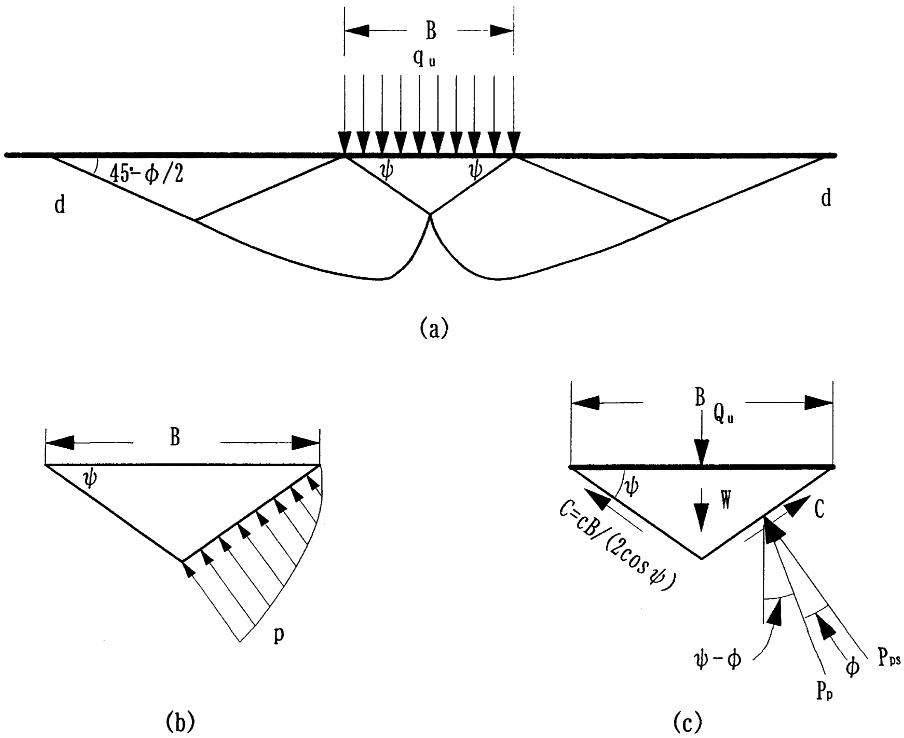

Figure 2 Bearing capacity of unsaturated expansive soil basement expressed by using swelling pressure (a) Bearing capacity of rough base; (b) Distribution of expansive earth pressure; (c) Forces on elastic wedge

where B is the width of footing in metres and a is the percent of clay in Equation (10). If $10a\cos\psi \gg 3B$ (as $(10a\cos\psi)/(3B) > 10$), the expansive lateral force for a strip footing can be written as follows,

$$P_{ps} = \frac{5p_sB}{6\cos\psi} \tag{13}$$

Substituting Equation (13) into Equation (11) and based on the Terzaghi formula, the ultimate bearing capacity of a strip footing in unsaturated expansive soils is given by

$$q_u = \frac{Q_u}{B} = c_0N_c + qN_q + \frac{1}{2}\gamma BN_\gamma + p_sN_s \tag{14}$$

where

$$\begin{aligned} N_c &= \tan\psi + \frac{\cos(\psi-\phi)}{\cos\psi\sin\phi}\left[e^{\left(\frac{2\pi}{3}+\phi-2\phi\right)\tan\phi}(1+\sin\phi)-1\right] \\ N_q &= \frac{\cos(\psi-\phi)}{\cos\psi}e^{\left(\frac{2\pi}{3}+\phi-2\phi\right)\tan\phi}\tan\left(45^* + \frac{\phi}{2}\right). \\ N_\gamma &= \frac{1}{2}\tan\psi\left[\frac{k_{p\gamma}\cos(\psi-\phi)}{\cos\psi\cos\phi}-1\right] \\ N_s &= \frac{5}{3} \end{aligned} \tag{15}$$

where $k_{p\gamma}$ is the coefficient of passive earth pressure for no cohesion or surcharge pressure. Equation (14) offers a method to calculate the bearing capacity of unsaturated expansive soils using the swelling pressure, instead of matrix suction. It can be seen from Equations (14) and (15) that the ultimate bearing capacity of an unsaturated expansive soil contains two parts. One is the ultimate bearing capacity of a saturated soil ($c_0 N_c + qN_q + \frac{1}{2}\gamma BN_\gamma$), and another is the ultimate bearing capacity expressed by swelling pressure ($p_s N_s$).

4. Results for Handan and Ningxia expansive soils

Handan expansive soil is found between the foot of Taihang Mountain and the North China Plain. The problems of Ningxia expansive soil are encountered in the middle route of the South-to-North Water Transfer project in China. The physical and mechanical properties of Handan and Ningxia expansive soils are summarized in Table 1.

4.1 TRIAXIAL TESTS

A series of unconsolidated undrained triaxial tests were performed on unsaturated samples of the Handan and Ningxia expansive soils prepared at are range of different water contents. In addition, tests were performed on saturated samples. The difference in shear strength between the unsaturated tests and the saturated tests was evaluated as the suction cohesion c_s.

The results are plotted in Figure 3. It can be seen that the results do follow a power law (since they show a linear relationship when plotted on log-log scale) which validates the form of Equation (4) relating suction cohesion to water content.

Also shown in Figure 3 is data for another Chinese expansive soil, Ankang. In Figure 3, the symbols I, II and III represent expansive soil with expansion potential of high, medium and low, respectively. It is seen from Figure 3 that the suction

Table 1. Physical and mechanical indexes

Index type	Handan	Ningxia
Water content w(%)	18–25	16–24
Unit weight γ (kNm^{-3})	20.0	19.8
Specific gravity G_s	2.71	2.70
Void ratio e	0.54	0.77
Degree of saturations S (%)	92	84
Liquid limit w_L(%)	44.0	50
Plastic limit w_p(%)	21.0	29
Percent of clay a (%)	27	20
Free swell δ_d (%)	77	64
Swelling pressure p_s(kPa)	158	100
Cohesion c_0 (kPa)	16.2	25
Angle of friction ϕ_u	10	14

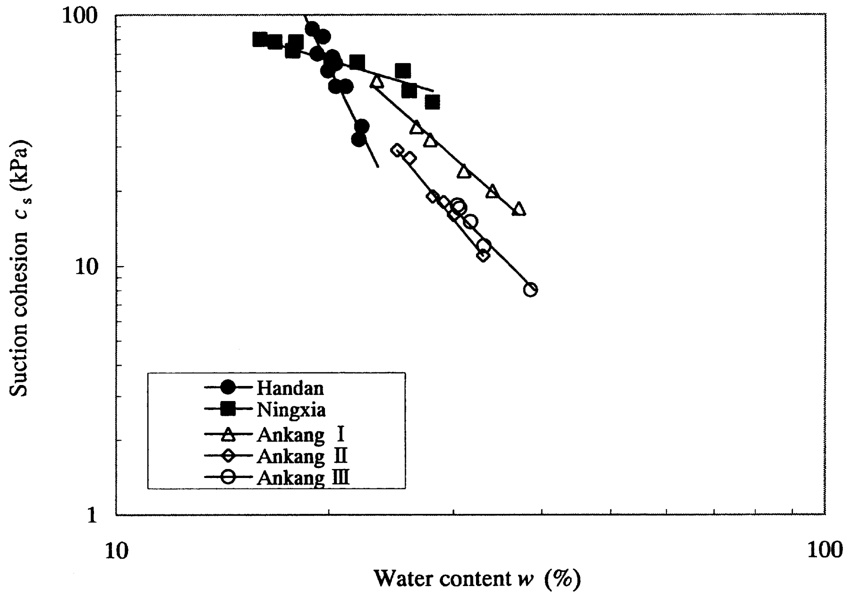

Figure 3 The relationship between suction cohesion and water content

cohesion of expansive soil decreases as the water content increases. The higher the expansion potential, the larger is the variation in total cohesion.

Figure 4 shows the values of angle of friction (in total stress terms) plotted against water content. The angle of internal friction was measured by using UU triaxial compression tests, with σ_3, of 50 kPa, 100 kPa and 200 kPa, respectively for each specimen. In addition to the data for Handan and Ningxia, results for Ankang are also included. It can be seen from Figure 4 that the angle of friction for Handan and Ningxia varied only slightly with water content and was nearly a constant for the expansive soils with low expansion potential. Thus, it is considered that the angle of friction is a constant for the soil with low expansion potential. The assumption will therefore be made that ϕ is constant for the Handan and Ningxia soils.

4.2 PLATE LOAD TESTS

In order to measure the bearing capacity of the foundation in unsaturated expansive soil, plate load tests were performed in Handan and Ningxia expansive soils. The plate load tests were proposed as follows:

(1) The plate size was 30 cm×30 cm (Figure 5);
(2) The loading increment in every step was 490N to measure the bearing capacity of foundation in unsaturated expansive soil, and 245N for the foundation immersed

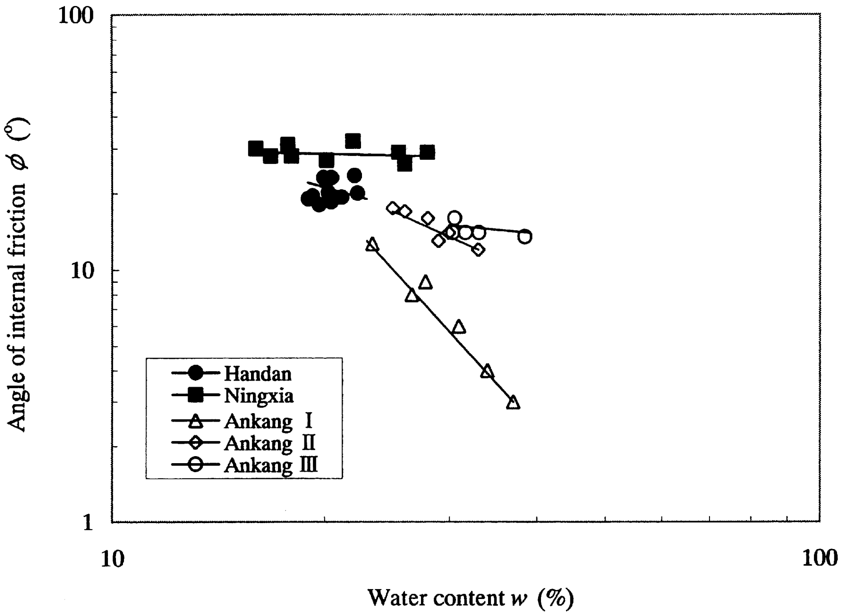

Figure 4 Variation of the angle of friction with water content

in water;

(3) When the settlement was less than 0.01 mm in an hour, the next step loading was exerted until the foundation failed. The settlement was measured using a precision leveling instrument.

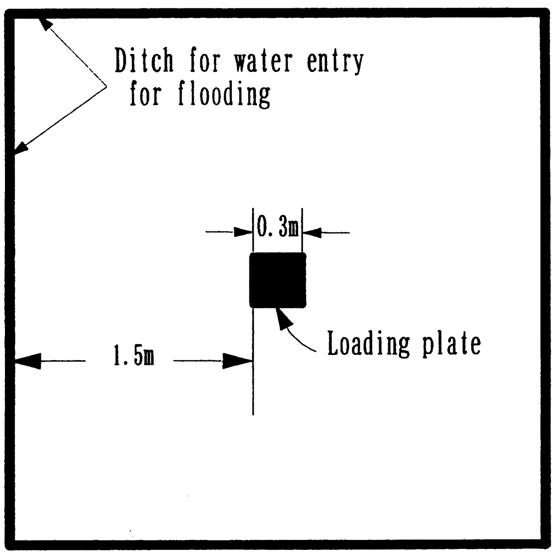

Figure 5 Sketch of plate of load test

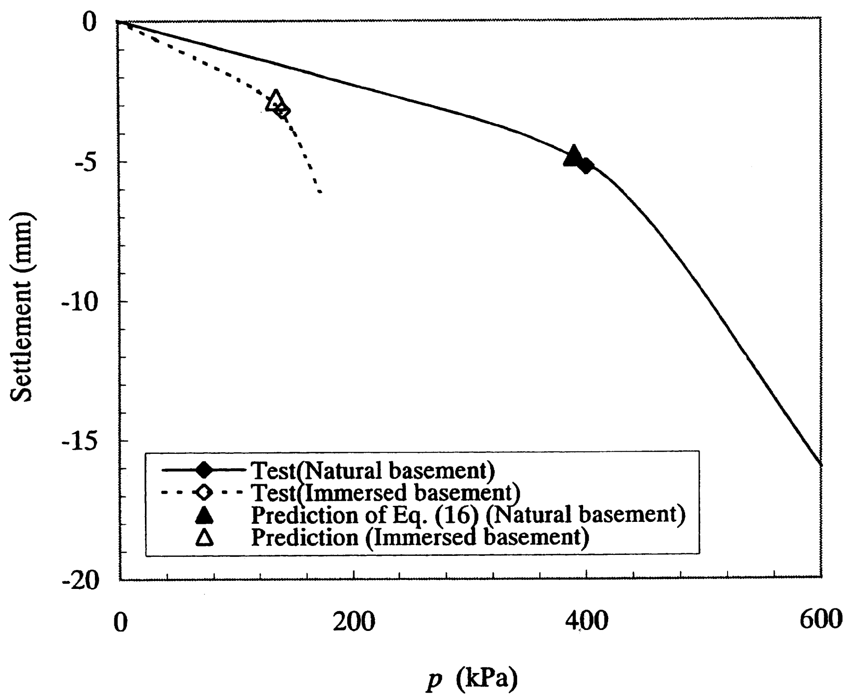

Figure 6 Bearing capacity of expansive soil in Handan (Measured data from Zhai et al., 1988)

(4) Water was supplied along the ditches around the loading plate (Figure 5). The uniformity of soil saturation was not measured after the test.

The measured results of plate load tests of the Handan expansive soil are shown in Figure 6. The ultimate bearing capacity of the unsaturated expansive soil was 400 kPa, which was measured in the plate load tests, and the ultimate bearing capacity was 140 kPa for the saturated soil immersed in water in plate load tests.

The results of plate load tests of the Ningxia expansive soil are shown in Figure 7. Collapse of the Ningxia expansive soil was found to occur in the inundated foundation when the load on the plate was larger than the swelling pressure in Figure 7. The ultimate bearing capacity of the unsaturated expansive soil was 420 kPa according to the results of plate load tests and the ultimate bearing capacity was 250 kPa for the saturated soil immersed by water.

4.3 BEARING CAPACITY RESULTS

Figure 8 shows the relationship between the bearing capacity and water content. Figure 2, for Handan and Ningxia and for other soils reported by Zhai et al.

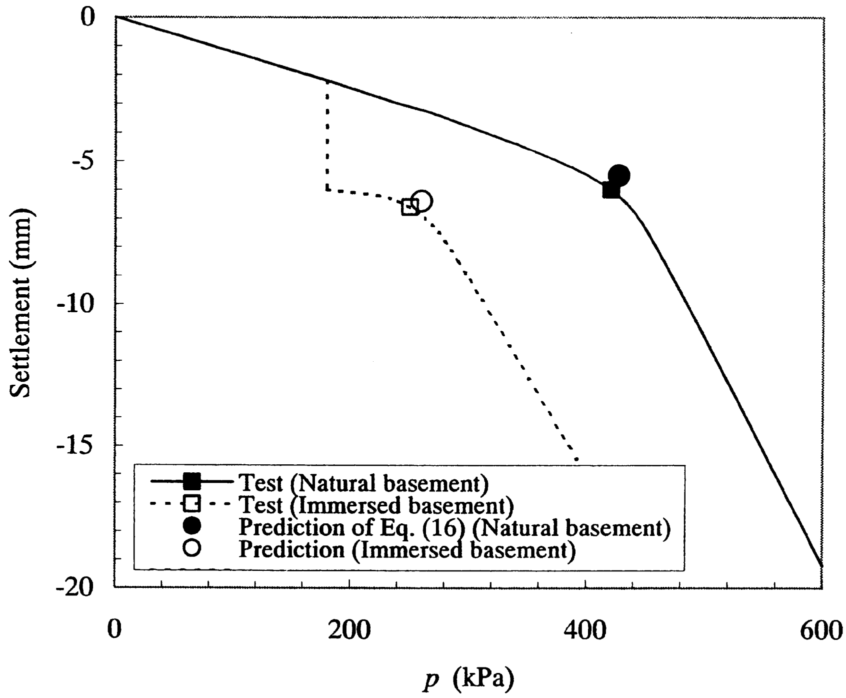

Figure 7 Bearing capacity of Ningxia expansive soil (Measured data from Wang, 1995)

(1988) shows the results of total bearing capacity and the bearing capacity due to the suction component from *in situ* plate load tests. The plate size and test procedures for the results of Handan expansive soil from Zhai et al. (1988) are the same as those applied in testing Ningxia expansive soils. The total bearing capacity was measured in the natural state in the area around the plate was then immersed to determine the bearing capacity in a saturated condition. The component due to suction, q_s, was evaluated by subtracting the saturated result from the total bearing capacity for the drier, natural state. From Figure 8a, it is seen that the lower are the water content of the unsaturated expansive soil, the larger is the bearing capacity. The relationship between q_s and water content is depicted in Figure 8b. It can be seen from Figure 8b that a power function exists between q_s, measured *in situ* and the water content of unsaturated expansive soil. The measured results in Figure 8b validates Equation (5) which expresses the power law relationship between q_s and water content.

Figure 9 shows the relationship between q_s and swelling pressure, p_s. It can be seen that the relationship is linear, as predicted by Equation (8). For these Chinese expansive soils the constant $k = 1.65$.

It should be noted that the degrees of saturation for the soils considered are relatively high (greater than 80%). This linear relationship might no longer hold for drier soils (with higher suctions).

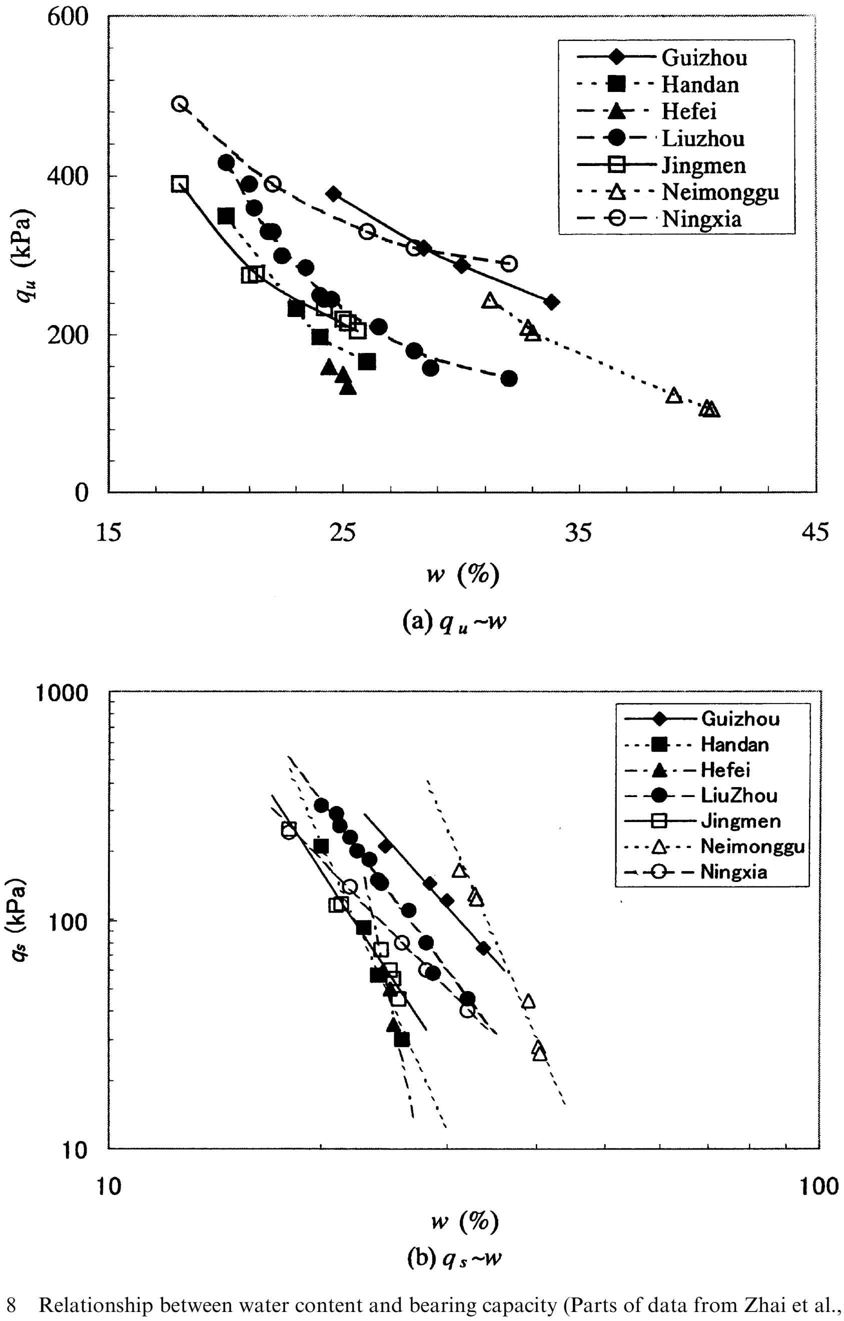

Figure 8 Relationship between water content and bearing capacity (Parts of data from Zhai et al., 1988)

4.4. COMPARISON OF PREDICTIONS WITH TEST RESULTS

The bearing capacity of the soil in the natural state has been predicted, based on the measured swelling pressures, using Equation (14). The bearing capacity for the

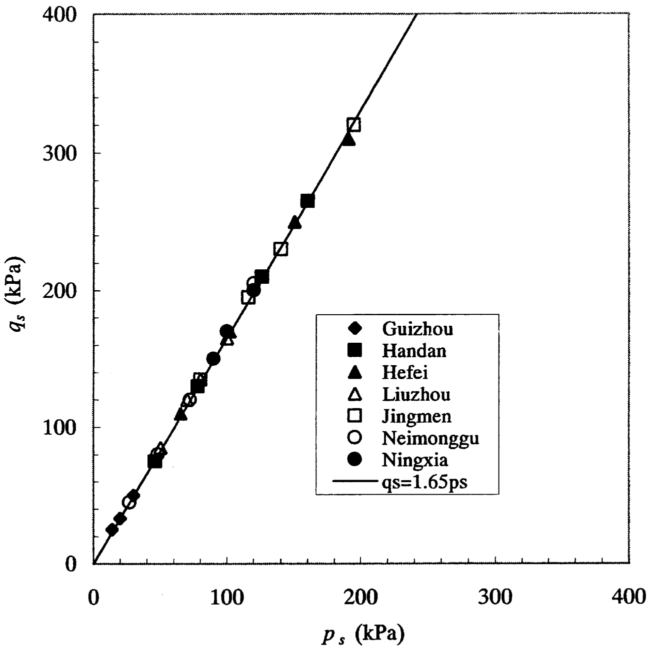

Figure 9 Relationship between swelling pressure and bearing capacity due to suction (Part of data from Zhai et al., 1988)

saturated state is based only on the first component of the bearing capacity (not including the swelling pressure term). For plate load tests, there was no surcharge ($q = 0$), and the item $\frac{1}{2}\gamma BN_\gamma$ was ignored because the value of $\frac{1}{2}\gamma BN_\gamma$ is small relative to the other items in Equation (14). Thus, the bearing capacity of natural soil by using Equation (14) is written as follows:

$$q_u = s_c c_0 N_c + p_s N_s \tag{16}$$

on the right side of Equation (16), $s_c c_0 N_c$ is the bearing capacity of the saturated soil, and $p_s N_s$ is the bearing capacity caused by the swelling pressure. $s_c c_0 N_c$ is used to calculated the bearing capacity of the foundation immersed in water.

For the Handan expansive soil, the following was obtained from laboratory test that $p_s = 158\,\text{kPa}$, $c_0 = 16.2\,\text{kPa}$ and $\phi = 10°$, which are shown in Table 1. According to Equation (15), it is found that $N_c = 8.35$ for $\phi = 10°$. The ultimate bearing capacity of saturated soil $(q_u)_{\text{sat}}$ is therefore 162.3 kPa calculated using the shape factor $s_c = 1.2$. The swelling pressure p_s equalled 158 kPa, and so the calculated ultimate bearing capacity of the unsaturated soil, q_u equalled 425.6 kPa, since $(q_u)_{\text{sat}} =$ 162.3 kPa in Equation (16). For Handan expansive soil, the bearing capacity calculated by Equation (16) is also shown in Figure 6. It is found that good agreement exists between the measured ultimate bearing capacity by the plate load tests and the calculated bearing capacity using Equation (16), as seen in Figure 6.

Table 2 Comparison of measured and calculated results of bearing capacity

	Measured results (kPa)		Calculated results (kPa)	
Testing points	Natural soil	Saturated soil	Natural soil	Saturated soil
Handan	400	140	425.6	162.3
Ningxia	420	250	478.7	312

From the laboratory test results shown in Table 1, the cohesion, internal friction angle and swelling pressure are 25 kPa, 14° and 100 kPa, respectively for Ningxia expansive soil. The following was obtained using Equation (15) that $N_c = 10.4$ for $\phi = 14^\circ$. The ultimate bearing capacity of saturated soil $(q_u)_{\text{sat}}$ is therefore 312 kPa calculated from $s_c = 1.2$, $C_0 = 25\,\text{kPa}$ and $N_c = 10.4$. Substituting $p_s = 100\,\text{kpa}$ and $(q_u)_{\text{sat}} = 312\,\text{kPa}$ into Equation (16), the ultimate bearing capacity of natural expansive soil in Ningxia is 478.7 kPa.

The bearing capacity measured by the plate load tests and the bearing capacity calculated from Equation (16) are summarized in Table 2. It is seen from Table 2 that the measured results in the plate load tests are slightly less than the calculated results from Equation (16) for the ultimate bearing capacity for Handan and Ningxia expansive soils.

5. Conclusions

Three conclusions can be obtained as follows, based on the soils of this study with degrees of saturation above 80%.

1. The bearing capacity of an unsaturated expansive soil is composed of two parts: the ultimate bearing capacity of a saturated soil and the ultimate bearing capacity caused by matric suction of unsaturated expansive soil.
2. The bearing capacity of an unsaturated expansive soil is related to the swelling pressure and water content. The lower the water content, the greater is matric suction, and the greater is the bearing capacity of an unsaturated expansive soil. The larger is the swelling pressure, the greater is the decrease of the bearing capacity when it is immersed in water.
3. A method to determine the bearing capacity of an unsaturated expansive soil is presented using swelling pressure in conjunction with undrained traxial testing. The bearing capacity of an unsaturated expansive soil can be evaluated by using proposed method without measuring matric suction or the angle, ϕ^b. The proposed methód is very promising according to the good agreement between predictions and measured results of in situ plate load test on Ningxia and Handan expansive soils, but some further verification is desirable.

The analysis is limited in two respects: (1) It is based on a total stress angle of friction which has little relationship to the real soil behavior. (2) Assumptions concerning the distribution of expansive lateral pressure are based on results, for a saturated expansive soil and are not borne out by observations.

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