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Exploration and Practice of Innovative Teaching of the Course Soil Mechanics and Foundation Engineering

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Abstract: Based on the analysis of the status quo in experimental teaching of soil mechanics, this paper discusses the disadvantages of the content setting and teaching mode. It proposes to reform the experimental teaching of soil mechanics in light of local characteristics with the aim to improve the quality of experimental teaching of soil mechanics, cultivate the hands-on skills and innovation ability of students, and strengthen experiment data processing and analysis. To provoke reflective thoughts and arouse the interests of the students and improve the level of experimental teaching of soil mechanics, the author attaches great importance to the shear strength test of root-soil composite by gathering soil samples in the field, preparing remolded soil samples, conducting the test on the basis of direct shear principles of soil, and processing and analyzing the data. To clear up the confusion among students over the calculation of punching shear bearing capacity of shallow foundation, the author independently develops a demo model for punching shear of shallow foundation in light of actual conditions of the school, and uses the model to teach Class 3 and Class 4 students, who major in civil engineering and enrolled in 2013, how the calculate punching shear bearing capacity of foundation and the optimal foundation height. The teaching results show that the two classes do better in calculating the punching shear bearing capacity of shallow foundation during the final exam than Class 1 and Class 2, and the x^2 test p <0.01. Hence, the self-made demo model for punching shear bearing capacity of shallow foundation can help students learn about the principles of punching shear calculation, and carry out punching shear calculation skillfully. Thus, the teaching pattern both arouses the interest in learning and improves the learning efficiency.

Keywords: *Soil mechanics experiment; Teaching reform; Shear strength test of root-soil composite; Shallow foundation; Punching shear; Demo model; Teaching effect*

1. Introduction

Soil Mechanics and Foundation Engineering is an important, fundamental course in civil engineering. In the aspect of soil mechanics, the course offers extensive and comprehensive knowledge, involving various points and numerous formulas. Besides, the principles and theories of soil mechanics are mostly developed on the basis of experiments. Therefore, experimental teaching of soil mechanics is an important means to help students understand the basic concepts, verify the fundamental principles, and explore the engineering application of soil mechanics. Nevertheless, many colleges and universities fail to achieve ideal effects in experimental teaching of soil mechanics.

To address the issue, many colleges and universities have put forward their own teaching reform plans. For example, JIA Cai-hong [3] proposes a comprehensive and designable experiment; In the reform of the teaching contents and modes of soil mechanics experiment, LIN Wei-an [9] achieves the desired effects by explaining magical phenomena of soil particles like the Brazil Nut Effect and with the aid of some simple magic; Liao Yuan [8] comes up with a four-level teaching system for soil mechanics experiment consisting of confirmatory experiment, comprehensive experiment, applied experiment and innovative experiment.

In the aspect of foundation engineering, there is a certain difficulty for new learners to understand some concepts and principles. For example, the punching shear failure and shearing failure of under-column pad foundation are very likely to cause confusion among students. Another example is the foundation height design, a common topic in the textbook [1, 11]. When it comes to the height design of under-wall strip foundation, the height of foundation section is calculated according to the shear strength; when it comes to the height design of under-column pad foundation, the height of foundation section is calculated according to the punching shear strength. However, neither the textbook nor related national norms explain the differences and relations between shear failure and punching shear failure. During course teaching, students are very likely to confuse and even misunderstand the two concepts. To solve the confusion, L.F. points out that the ultimate strength of reinforced concrete slabs is frequently governed by the punching shear capacity [4]. Salim researched the punching shear of the reinforced concrete materials [10]. Liang Fayun [7] tries to help students understand and master the concepts by analyzing the mechanism and surface mode of punching shear failure and shear failure, in combination with specific examples. In addition, assuming that the net reaction force of the foundation changes linearly, Zhao Shaofei [14] deducts the accurate formula for foundation punching shear force under the eccentric load. The results show that the calculation error of the punching shear force varies with the effective height of the foundation, and the difference between the maximum and minimum net reaction forces of the foundation, and that the maximum error may exceed 15%. If a pad foundation has a low effective height and a greatly varying net reaction force, the foundation height should be designed by the accurate formula for foundation punching shear force.

As one of the firsts to restore expressway slope vegetation in China, Yunnan Province has high vegetation coverage. Relying on this advantage, the author reforms the teaching of soil mechanics course, tries to test the shear strength of root-soil composite, and compares the results against the shear strength parameters of pure soil. In this way, the author avoids the drawbacks of the traditional teaching mode, which emphasizes on theory and neglects experiment, and increases the students' interests in participating in soil mechanics experiment, thereby achieving the purpose of the experimental teaching of soil mechanics. As for the calculation of punching shear bearing capacity of the foundation, the author uses a self-made teaching demo model to explain the principle of punching shear failure, to display the cone-shaped punching shear failure, and explains how to calculate punching shear bearing capacity with the aid of the demo model. The teaching effects are rather good.

2. Status quo in experimental teaching of soil mechanics:

2.1. Monotonous experiment contents:

In Kunming University, the experimental course of soil mechanics is a 1-week long independent compulsory course placed after the theoretical course of soil mechanics. The university only sets aside one week for experiments like the experiment on the basic properties of soil, the experiment on the liquid limit and plastic limit of soil, the soil compression experiment and soil direct shear experiment. The problem is that these experiments lack correlation and the monotony nature dampens the students' enthusiasm. Plus, the students have no chance to prepare soil samples as these have been prepared by the teacher before the experiment. Since every group of students uses the same soil samples in the experiment, they might copy each other's experiment reports.

2.2. Outdated experimental teaching mode:

Currently, the experimental teaching of soil mechanics generally follows these steps: Before the class, the teacher prepares the equipment and the soil sample; in class, the teacher stresses on difficult points and carries out demo experiment; then, the students are divided into groups to carry out experiments and write experiment reports while the teacher walks around and gives them instructions. Because the teacher has explained the purpose, process and phenomenon of the experiment beforehand, the students might not pay enough attention to these aspects during the experiment and learn much less than they should have learned. The waste of the opportunity to improve practical ability and analytical thinking goes against the original intent of experimental teaching of soil mechanics.

In short, the traditional experimental teaching mode of soil mechanics falls far short of the vision of cultivating high quality civil engineering talents with solid theoretical basis, strong practical ability, as well as innovative and entrepreneurial spirit. Thus, it is imperative to implement teaching reform. The philosophy of the experimental teaching of soil mechanics should be changed. For the purpose of cultivating the practical ability of students, the experimental teaching mode must be reformed in light of the characteristics of the discipline of soil mechanics.

3. Innovative experiment of soil mechanics:

Many studies [2, 5, 6, 13] have shown that, plant roots can improve the shear strength indices of soil. In consideration of the high vegetation coverage in Yunnan Province which is one of the firsts to restore highway slope vegetation in China [13], the author carries out root-soil composite shear strength test in experimental teaching of soil mechanics, and compares the results with the shear strength indices of pure soil, thereby arousing students interest in the experiment and improving their ability of doing scientific research.

Compared with pure soil shear strength test, the shear strength test of root-soil composite is an innovative experiment. Since the steps and data processing of the experiment are not provided in the Guide Book on Soil Mechanics Experiment, the students have to design the experiment on their own. Considering that the students are in the second semester of the sophomore year, they are less exposed to scientific research and in lack of the ability of doing scientific research independently.

Hence, the teacher decides to provide them with relevant literature on root-soil composite shear test so that the students could draft a report on sample gathering and sample-making procedures, experiment steps and data processing. The students are not allowed to proceed with the experiment unless the report is reviewed and approved by the teacher, and are responsible for gathering and making samples all by themselves. In this way, the students apply theory to practice, and have a better perceptual knowledge of soil, which helps them understand and accept the contents of the soil mechanics course, and lays the perceptual foundation for high-level innovative ability.

The direct shear of pure soil is tested in accordance with the traditional principle of soil mechanics experiment. See Table 1 for the experimental results. The data in Table 1 are plotted as a scatter (XY) plot and linearly fitted to get the linear trend line. See Figure 1 for the resulting shear strength curve of rootless soil. The data are fitted by Curve Expert to get the fitting equation of this line. The intercept of the straight line expressed by the equation on the vertical axis is the cohesion of the soil $c = 6.68kPa$. The angle of the straight line is the internal friction angle $\varphi = 22.8^{\circ}$.

***Table 1**: Measured Shear Strength of Rootless Soil*

Vertical Load (KPa)	Ergometer Coefficient	Ergometer Reading	Shear Strength (KPa)	Cohesion (KPa)	Internal Friction Angle (º)
50	1.783	13	23.179	6.68	22.8
100	1.823	30	54.69		
200	1.808	49	88.592		
300	1.86	71	132.06		

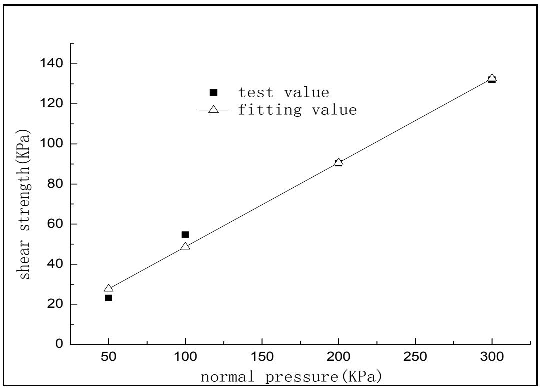

***Figure 1:** Test Values and Fitted Values of Shear Strength of Rootless Soil*

Root-soil composite samples should be made for comparative analysis of the effects of plant roots on the shear strength of soil. The samples are made by the students independently in reference to the literature provided by the teacher. This process, on the one hand, improves their ability of learning literature and mastering the latest research, and, on the other hand, enhances their hands-on ability and arouses their interest in soil mechanics experiments.

The students select the typical slope protection plants: bamboo reeds and Bermuda grass, and carry out direct shear tests on soils respectively containing 3, 6, 9 roots of each of these two plants. After obtaining the test data, the traditional way to seek the value of shear strength indices c and φ is to line up the dots drawn based on experimental data, acquire the internal friction angle φ of the soil according to the oblique angle of the straight line and acquire the cohesion c of the soil according to the intercept of the straight line on the vertical axis. However, this approach has a big error because it is constrained by the students' drawing ability. To solve this problem, students are required to obtain the shear strength indices of root-soil composite by data fitting. To handle the experimental data, the teacher provides them with the data processing software CurveExpert.

The students input the values of σ and τ obtained from the experiment, and then click on the option of linear fitting. The values of c and φ of the root-soil composite are obtained after simple data conversion, which avoids the error in the processing of experimental data. See Figure 2 for the results of data fitting when the soil has 3 roots of bamboo reeds. Data fitting reveals that the shear strength and the normal stress on the shear plane meet the Coulomb's law and offers the cohesion and internal friction angle in each group (Table 2).

***Table 2:** Shear Strength Indices of Each Sample Group*

Name of Plant	Number of Roots	Cohesion (KPa)	Internal Friction Angle (º)
Bamboo Reeds	3	14.87	24.33
	6	21.29	23.92
	9	31.80	24.98
Bermuda Grass	3	10.61	23.16
	6	17.79	23.60
	9	27.36	24.41

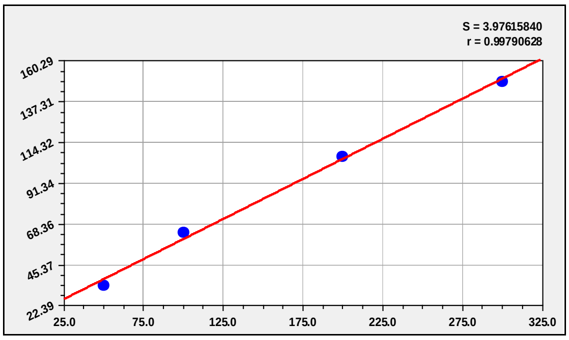

***Figure 2:** Direct Shear Test Results of the Soil with 3 Roots of Bamboo Reed*

According to the shear strength tests on pure soil and root-soil composite, plant roots have a great effect on the cohesion of the soil but a small impact to the internal friction angle. Specifically speaking, the internal friction angle varies rather narrowly as that of pure soil is 22.8º, while that of root-soil complex is 24.98º. In contrast, the cohesion changes significantly as that of root-soil complex is 31.80KPa, about 4.7 times of that of pure soil, which is 6.68KPa.

4. Punching shear calculation of flexible shallow foundation:

4.1. Calculation of punching shear bearing capacity:

The bottom size of step-shaped under-column pad foundation is $l \times b$, and the sectional size of the column is $a_t \times b_t$ (See Figure 3). When the short side size b of the bottom is greater than the sum of the column width b_t and twice the effective height of the foundation h_0, i.e. $b > b_t + 2h_0$, the punching shear bearing capacity at the junction of the column and the foundation should be checked.

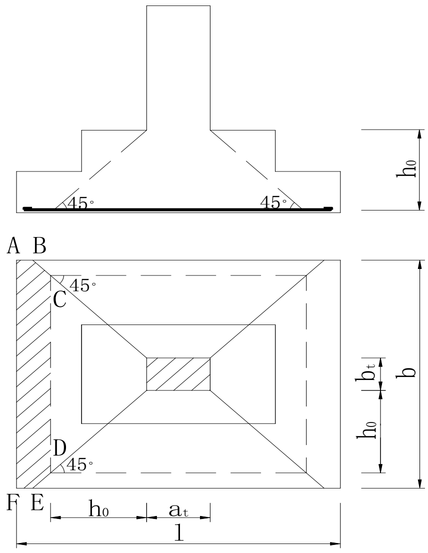

Figure 3: *Sketch Map on Calculation of Punching Shear Bearing Capacity of Step-shaped Under-column Pad Foundation*

When the foundation slab is punched, normal stress and shear stress are generated in the slab under local load or concentrated reaction force. When the normal stress and shear stress are combined, if tensile stress appears in the principal stress and exceeds the concrete tensile strength, oblique cracks would occur around the column, and eventually result in cone-shaped failure on oblique sections in the slab. It is called punching shear failure because its shape looks as if the slab is punched inside. The punching shear failure occurs in the shape of a cone with four trapezoidal punching shear surfaces (See Figure 4 and Figure 5). The surfaces are under tensile forces, the magnitude of which equals the product of the tensile strength of the concrete and the area of each punching shear surface. The teacher prints out the punching shear failure cone (See Figure 4) with a 3D printer to give the students a more intuitive description. Whereas each punching shear surface of the cone is a trapezoid, the length of the trapezoidal upper end is the side length of the column b_t, and the length of the lower end is $b_t + 2h_0$, and the effective height of the foundation is the height of the trapezoid $\sqrt{2}h_0$, then the area of the trapezoid is $\frac{b_t + b_t + 2h_0}{2} \times \sqrt{2}h_0 = \sqrt{2}(b_t + h_0)h_0$, and the tensile force on the punching shear surface is $\sqrt{2} f_t (b_t + h_0) h_0$.

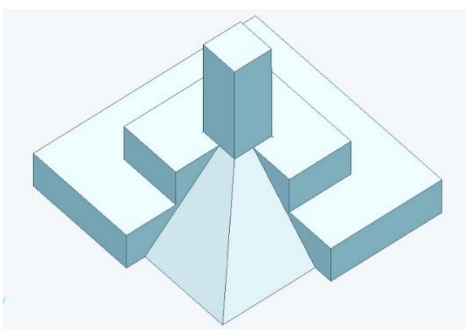

Figure 4: *Sketch Map of Punching Shear Failure*

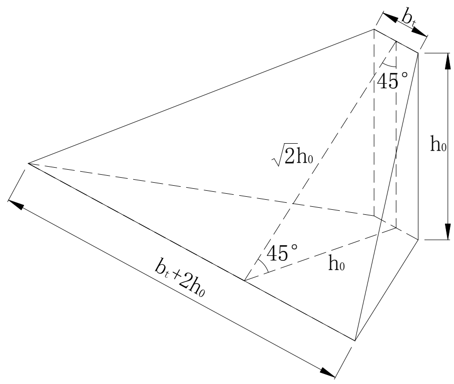

Figure 5: *Punching Shear Failure Cone at 1/4 of the Foundation*

According to the test results [12], when an under-column pad foundation has punching shear failure, the angle between the conical surface and the horizontal plane is 53°. As it is unnecessary to consider the error of b/h_0 due to thickening of the foundation slab, the data is multiplied with a reduction factor is 0.7. Then, in light of the influence of the foundation height, the data is further multiplied by the height coefficient β_{hp}, resulting in the following formula for calculation of the punching shear bearing capacity of shallow foundation:

$$F_l = 0.7\beta_{hp} f_t a_m h_0 \qquad (1)$$

Where, β_{hp} refers to the height coefficient of the section under punching shear. If h is no greater than 800 mm, β_{hp} is 1.0; if h is greater than 2,000mm, β_{hp} is 0.9; if h falls between 800mm and 2,000mm, β_{hp}=1-((h-800)/(12000)); f_t refers to the designed value of axial tensile strength of the concrete; a_m refers to the calculated length of the most negative side of the cone; h_0 refers to the effective height of the foundation; $F_l = p_j A_l$, where p_j refers to the net reaction force of the foundation at fundamental load combinations, while A_l refers to the action area of the punching shear force.

4.2. Determination of optimal foundation height:

Trial method is commonly used for the design of the foundation height, that is, check the foundation punching shear bearing capacity by Formula (1), keep adjusting the height till the bearing capacity is slighting greater than the punching shear force. This approach has a lot of disadvantages. Normally, it requires multiple trials, and the foundation height is not necessarily the optimal or most reasonable one, which affects the work quantity of the foundation, and in turn affects the cost of the project. Therefore, it is of great necessity to determine the optimal sizes of the foundation rapidly and accurately.

Based on Figure 3 and Formula (1), there is

$$a_m = b_t + h_o \qquad (2)$$

$$A_l = \left(\frac{l}{2} - \frac{a_t}{2} - h_o\right)b - \left(\frac{b}{2} - \frac{b_t}{2} - h_o\right)^2 \qquad (3)$$

Substitute Formula (2) and Formula (3) into Formula (1), there is:

$$p_j[\left(\frac{l}{2}-\frac{a_t}{2}-h_o\right)b-\left(\frac{b}{2}-\frac{b_t}{2}-h_o\right)^2] \qquad (4)$$
$$\leq 0.7\beta_{hp} f_t (b_t + h_0) h_0$$

In Formula (4), let $k = 0.7\beta_{hp} f_t / p_j$, there is:

$$h_0^2 + b_t h_0 - \frac{\eta b_t^2}{4(1+k)} \geq 0 \qquad (5)$$

Where, η is the size coefficient, $\eta = (2n-1)w^2 - 2(m-1)w - 1$. $n = \frac{l}{b}$, $m = \frac{a_t}{b_t}$, and $w = \frac{b}{b_t}$. η can either be calculated according to the above formula, or be looked up from Table 3 based on the values of *n*, *m* and *w* and by the excel-based data calculation program.

Let $\lambda = \sqrt{1+\frac{\eta}{k+1}}$ and $\zeta = \frac{\lambda-1}{2}$, and solve Formula (5):

$$h_0 \geq \zeta b_t \qquad (6)$$

***Table 3:** Size Coefficient η*

n	m	w	η
1.0	1.0	1.5	1.25
1.0	1.1	1.6	1.24
1.0	1.2	1.7	1.21
1.0	1.3	1.8	1.16
1.0	1.4	1.9	1.09
1.0	1.5	2.0	1.00
1.1	1.0	2.1	4.29
1.1	1.1	2.2	4.37
1.1	1.2	2.3	4.43
1.1	1.3	2.4	4.47
1.1	1.4	2.5	4.50
1.1	1.5	2.6	4.51
1.2	1.0	2.7	9.21
1.2	1.1	2.8	9.42
1.2	1.2	2.9	9.61
1.2	1.3	3.0	9.80
1.2	1.4	3.1	9.97
1.2	1.5	3.2	10.14
1.3	1.0	3.3	16.42
1.3	1.1	3.4	16.82
1.3	1.2	3.5	17.20
1.3	1.3	3.6	17.58
1.3	1.4	3.7	17.94
1.3	1.5	3.8	18.30
1.4	1.0	3.9	26.38
1.4	1.1	4.0	27.00
1.4	1.2	4.1	27.62
1.4	1.3	4.2	28.23
1.4	1.4	4.3	28.84
1.4	1.5	4.4	29.45
1.5	1.0	4.5	39.50
1.5	1.1	4.6	40.40
1.5	1.2	4.7	41.30
1.5	1.3	4.8	42.20
1.5	1.4	4.9	43.10
1.5	1.5	5.0	44.00

In the design of the optimal foundation height, the author firstly obtains the value of k according to the concrete strength grade and the net reaction force of the foundation by formula $0.7\beta_{hp}f_t/p_j$, secondly calculates the value of η according to foundation slab size and column cross-sectional size by formula $(2n-1)w^2 - 2(m-1)w - 1$ or by Table 3, and finally calculates the minimum effective height of the foundation h_0 by $\lambda = \sqrt{1+\frac{\eta}{k+1}}$, $\zeta = \frac{\lambda-1}{2}$ and Formula (6), thereby determine the minimum height of the foundation according to the thickness of the rebar protective layer.

4.3. Teaching effect:

In our university, the calculation of shallow foundation punching shear capacity is traditionally explained with transparencies. The traditional method is still used to teach Class 1 and Class 2 students, who major in civil engineering and enrolled in 2013. In order to compare the teaching effect, the author uses the self-made demo model to teach Class 3 and Class 4 students, who also major in civil engineering and enrolled in 2013. By comparing the correct answer rates of the two groups of students on relevant questions in the final exam, the author concludes that the x^2 test p <0.01 is of statistical significance (See Table 4).

***Table 4:** Comparison between Correct Answer Rates of Students in Classes 1&2 and Classes 3&4 (majoring in civil engineering and enrolled in 2013)*

Group	Correct	Wrong	In Total	Correct Rate (%)
Classes 1 & 2	50	47	97	51.4
Classes 3 & 4	84	36	120	69.8
In total	134	83	217	61.8
x^2=7.73, p<0.01 $p < 0.01$				

5. Conclusion

In consideration of the high vegetation coverage in Yunnan Province, the author reforms the contents and modes of experimental teaching of soil mechanics by testing the shear strength of root-soil composite on the basis of traditional direct shear test. The reform changes the teaching ideas, overcomes the monotony of traditional teaching method, and prevents the students from learning mechanically. In particular, the new teaching mode arouses strong interest among the students in learning, and improves their hand-on, teamwork and research abilities.

The demonstration by self-made model and explanation of mechanics principle help the student develop an intuitive understanding of the punching shear surfaces in a shallow foundation under punching shear, understand the calculating principle of punching shear bearing capacity, and learn how to determine the optimal height of the foundation. Thus, the teaching pattern both arouses the interest in learning and improves the learning efficiency.

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