Research Article

Relationship between the Shear Strength and the Depth of Cone Penetration in Fall Cone Tests

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Received 20 August 2020; Revised 17 November 2020; Accepted 25 November 2020; Published 12 December 2020

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The determination of liquid limit is of great significance in the engineering classification of soil and the selection of the control standard of highway subgrade packing and compactness. Based on the research achievements of many scholars on the relationship between the shear strength and the depth of cone penetration in fall cone tests in the liquid limit tests, the process of penetration was analyzed according to the Law of Conservation of Energy, and the expression of \( K \) was derived. Then, the expression was verified by the experimental data of different scholars and the existing data of various countries and institutions. And, the results were also compared with those obtained by the previous scholars using limit equilibrium theory. The results indicate that the new expression is in good agreement with the experimental results. \( K \) can be predicted well. And so, the shear strength can be calculated based on the depth of cone penetration, and then, the experimental value of the shear strength can be compared with the calculated value through laboratory tests. The influence of cone weight and cone angle on the shear strength calculation was analyzed. In addition, the liquid limit index of different standards was discussed based on the expression of \( K \), and suggestions on how to achieve relative combination of different codes and standards were raised, which was very helpful for international communication.

1. Introduction

Liquid limit is an extremely important physical index of cohesive soil. It is one of the main parameters for soil engineering characteristics evaluation and engineering classification of cohesive soil [1–3]. As soil mechanics have advanced, more accurate methods of testing soils (both in the laboratory and in the field) have been developed and less reliance has been placed on the results of index tests. Nevertheless, they still played a major role in the assessment of any soil [4]. In addition, the determination of the liquid-plastic limit is of great significance for the selection of subgrade fillers and the compaction control in highway construction [5–7].

In terms of definition, the liquid limit is the demarcation of the soil strength from “nothing” to “something.” In other words, the liquid limit is the water content of remoulded soil at minimum measurable shear strength [8]. The water content of the loess determined the shear strength and the type of failure of the loess, and the mechanical strength and stress-strain characteristics of the loess were very different with different water content [9]. Some scholars studied the compaction and strength characteristics of high liquid limit subgrade fill, and the results showed that the cohesive force \( c \) decreases with increasing water content when the water content is greater than the optimal water content under the same compaction degree. Therefore, the liquid limit test of soil could also be regarded as an indirect shear test [10].

The main methods for determining the liquid limit are the fall cone test and percussion test. Among them, the fall cone test is very convenient and easy due to its small human error and good reproducibility, and the fall cone test is essentially a test of the shear strength of soil samples, which is also more widely used [11–13]. Many studies have been
conducted on the fall cone test, and lots of experimental studies had been conducted on the relationship among water content \( \omega \), shear strength \( \tau \), and cone penetration depth \( h \) in the test of liquid limit [14–24]. Hansbo proposed the undrained shear strength \( \tau \) was proportional to the product of cone weight \( P \) and the reciprocal of the square of cone penetration depth \( h \) that is as follows [14]:

\[
\tau = K \cdot \frac{Q}{h^2}
\]

(1)

where \( Q \) is the cone weight, \( h \) is the cone depth, and \( K \) is a proportional parameter.

Hansbo also studied the selection of \( K \), and he stated that the parameter depended not only on the cone angle but was also influenced by the rate of shear and the sensitivity of the clay [14]. A large number of experiments were conducted by a number of scholars to verify equation (1), and the influencing factors of \( K \) of remolded soil were discussed too [4, 15, 18]. It was found that in addition to the cone angle \( \alpha \), the specific type of soil was also an influencing factor, which could be represented as the friction coefficient \( \mu \) between the cone and the soil. Wood made up some experiments based on the experiments of Karlsson, and the test results also verified the above viewpoints [15, 25]. However, no studies have been conducted on how the cone angle \( \alpha \) and the friction coefficient \( \mu \) affect the \( K \).

According to the static equilibrium analysis of the final state of the fall cone, the cone penetration process may be simplification as a two-dimensional problem, and the cone is in a static state. At the moment of release, the cone begins to suffer the resistance of the soil to the cone [28]. With the increase of the cone penetration depth \( h \), the cone is in accelerated motion with a decreasing acceleration. Then, when the cone head penetrates to a certain critical depth \( H \), the resistance of soil is equal to the weight of the cone and the cone is in the limited equilibrium state at this moment. Then, the cone continues to penetrate downwards under the action of inertia. In this process, the cone makes a decelerated motion with an increasing acceleration. When the final velocity reduces to zero, the cone changes from the moving state to the static state. Also, the resistance of cone changes from dynamic friction resistance to static friction resistance, which is exactly equal to its own weight to achieve a new balance [14, 15, 18, 25]. The specific equation of acceleration and speed in this process are as follows:

\[
v = \sqrt{2gh \left[ 1 - \left( \frac{h}{Z} \right)^2 \right]},
\]

(2)

\[
a = g \left[ 1 - 3 \left( \frac{Z}{h} \right)^2 \right].
\]

(3)

The critical depth \( H \) is as follows:

\[
H = \frac{Z}{\sqrt{3}}.
\]

(4)

where \( v \) is the velocity of cone, \( g \) is the gravitational acceleration, \( a \) is the acceleration of cone, \( h \) is the depth of cone penetration, \( Z \) is the final depth of cone penetration, and \( H \) is the critical depth of cone penetration (the resistance of soil is equal to the weight of cone).

According to equations (2)–(4), the acceleration \( a \) and velocity \( v \) with the depth \( h \) of cone penetration can be drawn, as shown in Figure 1.

In the process of cone drop, the cone was analyzed according to the Law of Conservation of Energy, and it can be seen that the gravitational potential energy of the cone is converted into the work done by the soil. Therefore, the relationship between the shear strength \( \tau \) and the depth \( h \) of cone penetration can be derived from this relationship. The mechanical analysis diagram of the cone is shown in Figure 2 [14].

The force analysis of the cone shows that, in the initial state, the cone is in a static state. At the moment of release, the cone is in a free-falling state, the value of maximum acceleration is one \( g \) and its direction is downward, the velocity increases from zero, and the cone is undergoing the uniformly accelerated motion. As the cone tip just penetrates into the soil, the cone begins to suffer the resistance of the soil to the cone [28]. With the increase of the cone penetration depth \( h \), the cone is in accelerated motion with a decreasing acceleration. Then, when the cone head penetrates to a certain critical depth \( H \), the resistance of soil is equal to the weight of the cone and the cone is in the limited equilibrium state at this moment. Then, the cone continues to penetrate downwards under the action of inertia. In this process, the cone makes a decelerated motion with an increasing acceleration. When the final velocity reduces to zero, the cone changes from the moving state to the static state. Also, the resistance of cone changes from dynamic friction resistance to static friction resistance, which is exactly equal to its own weight to achieve a new balance [14, 15, 18, 25]. The specific equation of acceleration and speed in this process are as follows:

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According to the Law of Conservation of Energy, the gravitational potential energy released by the cone into the soil should be equal to the sum of the work done by the cone shear stress and the work done by the cone normal stress on the soil, which is as follows:

\[
PZ = \int_0^Z \tau A \cdot dl + \int_0^Z \sigma A \cdot ds,
\]

(5)

where \( Z \) is the final depth of cone penetration and \( A \) is the contact area between the cone and the soil, and their calculation is as follows:

\[
A = \frac{1}{2} L \cdot R = \pi rl = \frac{\pi h^2 \tan(\alpha/2)}{\cos(\alpha/2)},
\]

(6)

\[
dl = \frac{dh}{\cos(\alpha/2)},
\]

(7)

\[
ds = \sin \frac{\alpha}{2} \cdot dh.
\]

(8)

Assuming that the shear strength of the soil is constant during the cone penetration process, as the resultant force of the soil on the cone is always in the vertical direction, the analysis of the force on the cone shows the following:
analysis shows that a cone which would be in equilibrium at a penetration \( H \) when slowly lowered would penetrate \( Z \) if allowed to fall under its own weight \( P \) (starting at rest with the cone tip touching the soil surface) [14, 18, 29]. The geometric relationship between \( Z \) and \( H \) is as follows:

\[
Z = H \cdot \sqrt{3}.
\]  

(12)

So,

\[
K = \frac{\cos^2 \left( \frac{\alpha}{2} \right)}{\pi \tan \left( \frac{\alpha}{2} \right) \left( 1 + \sin^2 \left( \frac{\alpha}{2} \right) \right)}.
\]  

(13)

The expression of \( K \) is obtained, as shown in equation (13). By applying \( H \) to equation (11), the shear strength under liquid limit can be obtained, but all the results calculated are far higher than the experimental values. It is therefore questionable whether dynamic analysis is effective or whether static analysis should be used. Quasi-static conditions may apply if the viscous effect is sufficient to slow the falling cone velocity [18]. Therefore, for the calculation of shear strength \( \tau \), take the depth \( h = Z \) and put \( K \) together into equation (1) to obtain the following equation:

\[
\tau = \frac{\cos^2 \left( \frac{\alpha}{2} \right) \cdot P}{\pi \tan \left( \frac{\alpha}{2} \right) \left( 1 + \sin^2 \left( \frac{\alpha}{2} \right) \right) \cdot h^2}.
\]  

(14)

Assuming the final state is the limit equilibrium state and the expression of the relationship between shear strength \( \tau \) and depth \( h \) of fall cone is derived based on the static equilibrium relationship as follows [26]:

\[
\tau = \frac{\cos^2 \left( \frac{\alpha}{2} \right) \cdot P}{\pi \tan \left( \frac{\alpha}{2} \right) \cdot h^2}.
\]  

(15)

Thus,

\[
K = \frac{\cos^2 \left( \frac{\alpha}{2} \right)}{\pi \tan \left( \frac{\alpha}{2} \right)}.
\]  

(16)

The result is different from that derived in this paper.

3. Comparison of Calculated and Experimental Values of \( K \)

For the specific value of \( K \), Hansbo conducted the fall cone test for 60° cone and obtained \( K_{60} = 0.30 \) [14]. Then, Karlsson did the cone test and shear test for cone angle \( \alpha = 30° \) and \( \alpha = 60° \) with the six soils, respectively, and the corresponding values of \( K \) were calculated by the known cone weight \( P \), the shear strength \( \tau \), and the depth \( h \) of cone penetration obtained from the tests [15]. The average values of \( K \) were obtained at the last. Wood made some additional experiments that three soils were tested for four cone angles (30°, 45°, 60°, and 75°) based on the experiments of Karlsson, and the corresponding values of \( K \) were calculated accordingly [25]. All these experimental results are shown in Table 1.

In order to verify the validity of equation (13), four cone angles \( \alpha \) (30°, 45°, 60°, and 75°) were substituted into equations (13) and (16), too. The values of \( K \) calculated are shown in Table 1, too.
Figure 3 gives the comparison between the experimental results and calculated results. As shown in Figure 3, the results given in equation (13) which was derived by the Law of Conservation of Energy are highly consistent with the experimental results of most soil, while the results given in equation (16) which was derived by the static equilibrium are generally higher than the experimental results. Thus, the validity of equation (13) is verified. The comparison also shows that the cone angle \( \alpha \) is an important factor which could affect the values of \( K \). The values of \( K \) gradually decrease as the cone angle \( \alpha \) gradually increases. For the friction coefficient \( \mu \), equation (13) cannot directly explain its influence on the values of \( K \). In addition, it can also be seen from Figure 3 that when the cone angle \( \alpha \) is small, the calculated values are higher than the experimental values, and then, the values of \( K \) are gradually close to the average of the experimental values as the cone angle \( \alpha \) gradually increases.

### 4. Comparison of Calculated and Tested Values of Shear Strength in the Specification

Referring to different regulations and standards of the geotechnical testing method, a comparison between the calculated shear strength by test standards and the experimental strength results [4, 15, 30–33] was conducted based on equation (14) (see Table 2 for details).

It can be seen from Table 2 that the calculated results of the shear strength \( \tau \) obtained by equation (14) are highly consistent with the experimental results obtained by different scholars, and almost all calculated values are within the range of the experimental values. But, the results calculated by equation (15) are generally higher than the experimental values, which further verifies the accuracy of \( K \) given by equation (13).

### 5. Comparison of Calculated and Tested Values of Shear Strength in Laboratory Tests

Three kinds of soils (Guizhou red clay, Shaoxing sandy soil, and Shaoxing undisturbed silt soil) were selected for laboratory tests to verify the relationship between cone penetration depth and shear strength. Firstly, the liquid and plastic limit test was carried out on three kinds of soil to obtain the relationship between coning depth and water content. Then, the vane shear tests were used to measure the shear strength of three kinds of soil under different water content. Through two kinds of tests, cone penetration depth \( h \) was associated with shear strength \( \tau \) and compared with deduced equation (13), and the results are shown in Figure 4:

As shown in Figure 4, the results of the experiment on different types of soil were consistent with the theory of cone penetration depth \( h \) and shear strength \( \tau \) derived in this study and had nothing to do with the specific type of soil, which further clarified the accuracy of equation (13). In addition, it is also found that with the increase of the cone penetration depth \( h \), the experimental values are more consistent with the theoretical values, indicating that, when the cone penetration depth \( h \) is low, namely, the water content \( w \) is low, the difference in the test error may occur due to the inconsistency in the porosity ratio and the degree of compaction caused by artificial sample installation.
6. Error Analysis of Fall Cone Test

In the experimental process, there are two main sources of error, namely, the error of cone weight and the error of cone angle due to factors such as production process error and wear during use. The effects of these two factors on shear strength are discussed below.

6.1. Error Analysis of Shear Strength Test Caused by Cone Weight.

The cone weight error may occur due to production accuracy, experimental wear, unclean cone, and improper storage. In order to determine the influence of cone weight error on liquid limit test results, the standard for the soil test method in China [32] was taken as an example: the standard cone weight was 76 g, the range of cone weight error $\Delta P$ was $\pm 5$ g, and then, the error of shear strength value corresponding to liquid limit standard could be calculated according to the derived equations (13) and (14).

As shown in Figure 5, there is a good linear relationship between the cone weight error $\Delta P$ and the error of shear strength, and the error generated by the increase or decrease of cone weight is nearly the same: the shear strength error corresponding to $\Delta P = \pm 5$ g is 6.58%. Therefore, whether the cone weight $P$ is accurate or not has some impacts on the experimental results. For the cone weight $P = (76 \pm 1)$ g, the error to the results is about 1.3%, with a relatively small impact.

6.2. Error Analysis of Shear Strength Test Caused by Cone Angle.

The cone is prone to wear during use, resulting in inaccurate cone angles. In order to determine the influence of cone angle error on liquid limit test results, the shear strength error caused by cone angle wear in the tests was analyzed below. The specific results are shown in Figure 6. The reference cone angle $\alpha$ is selected as 30° based on the standard of the soil test method in China [32], and the changes of the cone angle are $\Delta \alpha = \pm 5^\circ$.

As shown in Figure 6, the degree of error caused by the increase or decrease of the cone angle is different. The errors tend to be flat as the cone angle increases, and the error heavily increases as the cone angle decreases. Therefore, the cone angle $\alpha$ has a great influence on the experimental results. For the cone angle $\alpha = (30 \pm 1)^\circ$, the error caused by the result is about 4.3%, which is much larger than the influence of the cone weight. This result is very close to the conclusion obtained by Houlsby’s experiment [18], in which he used BS (80 g, 20 mm, 30°). This also verifies the validity of the equations (13) and (14) derived above.

7. Discussion on Liquid Limit Indicators of Different Standards Based on the Expression of $K$

In order to more intuitively observe the influence of the cone angle $\alpha$ on the shear strength $\tau$, the variation curves of shear strength $\tau$ with $P/h^2$ under four cone angles $\alpha$ (30°, 45°, 60°, and 75°) are calculated according to equation (1) and the derived expression of $K$ (equation (13)) (see Figure 7 for details).

The values of $K$ are the same for the same cone angle. Therefore, as shown in Figure 7, the shear strength $\tau$ has a linear relationship with $P/h^2$ at the same cone angle, and its slope is the value of $K$ corresponding to the cone angle $\alpha$. According to Figure 7, the liquid limit of different standards from the shear strength can be compared and unified. Firstly, the shear strength $\tau$ corresponding to the liquid limit standard of a certain specification is selected, and then, the values of $P/h^2$ corresponding to other different angles are determined according to the shear strength

| Standards category | Experimental value of $\tau$ (kPa) | Calculated value of $\tau$ (equation (14)) (kPa) | Calculated value of $\tau$ (equation (15)) (kPa) |
|--------------------|-----------------------------------|-----------------------------------------------|-----------------------------------------------|
| Sweden (60 g, 60°, 10 mm) | 1.5–2.1 [15] | 1.94 | 2.41 |
| BS (80 g, 30°, 20 mm) | 1.6 [30] | 2.04 | 2.18 |
| ΓOCT (76 g, 30°, 10 mm) | 8.5 [31] | 7.75 | 8.27 |
| GB/T 50123-2019 (76 g, 30°, 17 mm) | 1.3–2.8 [32] | 2.68 | 2.86 |
| JTG E40-2007 (100 g, 30°, 20 mm) | 1.2–2.7 [33] | 2.55 | 2.72 |

Figure 4: Comparison of experimental and calculated values of shear strength $\tau$. 

Figure 5: Shear strength $\tau$ and cone penetration depth $h$ relationship

Figure 6: The degree of error caused by the increase or decrease of the cone angle is different.
value, so as to determine the corresponding cone penetration depth $h$. According to the cone penetration depth corresponding to the liquid limit in the fall cone test in the standards of geotechnical test methods in China [32], the shear strength corresponding to the liquid limit can be calculated as $\tau = 2.6 \text{kPa}$. Then, the values of $P/h^2$ corresponding to the other angles are calculated (the dashed line shown in Figure 7). Also, according to the standard cone weight used in each standard, the corresponding cone penetration depth can be obtained. The results are shown in Table 3.

As shown in Table 3, the standard for the soil test method in China [32] is highly consistent with that of the test methods of soils for highway engineering of the Ministry of Transport [33]. However, there are still some differences between the calculated values and the standard values in the other specifications mentioned above, especially the standard of FOCT whose calculated value is almost twice the standard value. In this way, in the international communication, the data of all parties cannot be compared quickly and effectively. Therefore, in order to communicate internationally conveniently, the penetration depth calculated based on the equations (13) and (14) deduced in this paper can be selected as the standard.

8. Conclusion

The influence of the cone angle $\alpha$ on the values of $K$ was explained very carefully and intuitively by the expression of $K$, which was derived from the Law of Conservation of

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**Figure 5:** Errors caused by variation of cone weight $P$.

**Figure 6:** Errors caused by variation of cone angle $\alpha$. 
Energy based on the dimensional analysis of the fall cone by former scholars before. It was verified not only theoretically but also in good agreement with the test results of different scholars, the data of different geotechnical test standards, and the laboratory test results.

The errors of the cone weight $P$ and cone angle $\alpha$ on the experimental results were analyzed and compared. It was found that the variation of the cone angle had a greater influence on the experimental results. In general, the error on the result was about 4.3% for the cone angle $\alpha = (30 \pm 1)^\circ$; the influences caused by the variations in cone weight were relatively small, and the error on the result was about 1.3% for the cone weight $P = (76 \pm 1)$ g. In addition, the liquid limit index of different standards was discussed based on the expression of $K$, and suggestions on how to achieve relative unification of different codes and standards were put forward, which was very helpful for the international communication.

As for the influence of the friction coefficient $\mu$, the current geotechnical test method standards clearly stipulate that a thin layer of Vaseline should be applied to the surface of the cone before testing. This treatment can reduce the effect of the cone surface roughness effectively.

**Data Availability**

The data used to support the findings of this study are available from the corresponding author upon request.

**Conflicts of Interest**

The authors declare that they have no conflicts of interest regarding the publication of this paper.

**Acknowledgments**

The authors are grateful to the National Natural Science Foundation of China (Grant no. 41702329), the Scientific Research Fund of Hunan Provincial Education Department (Grant no. 17B097), Department of Natural Resources of Hunan Province (Grant no. 2020-15), and the Key Laboratory of Soft Soils and Geoenvironmental Engineering of the Education Ministry of China (Grant no. 2016P05) for their financial support.

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