The Analysis of The Impact of Liquid Limit on Mechanical Properties of Clayey Soil

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Abstract. This article introduces the importance of the liquid limit of soil. The liquid limit largely determines the plasticity index and liquidity index of soil, which directly affects the classification and denomination of the soil. It also makes an analysis of the impact of liquid limit on the state of clayey soil and its mechanical indicators. Even if the water content is high and the porosity is large, as long as the water content does not exceed the liquid limit, it cannot be named silt soil. Under the same conditions, the higher the liquid limit, the harder the state of the soil, the higher the undrained strength and bearing capacity, and the smaller the coefficient of consolidation, but the liquid limit has less impact on the compression coefficient and compression modulus.

1. Introduction
With the change of water content, clayey soil shows different states. When the water content is large, the soil shows slurry shape; with the decrease of water content, the slurry thickens and gradually becomes plastic soil block, i.e. plastic state; when the water content decreases again, the soil becomes semi-solid, i.e. semi-solid state; when the water content decreases further, the soil becomes solid, i.e. solid state. The changes of state reflect the results of the interaction between soil and water. When the water content in the soil is large, the soil particles are separated by free water, and the soil is in liquid state. When the water content is reduced to a situation that most of the soil particles are separated by weak absorbed water, the soil particles are staggered under the action of external force, while the connection between the particles is not lost, and the soil is in plastic state where the soil is considered to have plasticity. When the water content decreases again, the film of weak absorbed water becomes thinner, the viscosity increases, and the soil changes into semi-solid state. When the soil mainly contains strong absorbed water, the soil is in solid state [1-2].

When we study the consistency state of clayey soil, we need to study the critical water content of soil changing from one physical state to another as a quantitative criterion. Therefore, with the following definition, the critical water content of plastic state and liquid state is called liquid limit, which is expressed by wL; the critical water content of plastic state and semi-solid state is called plastic limit, which is expressed by wP. At the same time, the plasticity index IP and liquidity index IL are defined.

The plasticity index is closely related to the particle size of the soil. The higher the clay content is, the larger the specific surface area of the soil is and the larger the plasticity index is. According to these definitions, fine-grained soil can be denominated and classified. The liquidity index of soil reflects the consistency state of clayey soil, which is not only related to the plasticity index of soil, but also related to the water content.
In general, testing the liquid limit of clayey soil is simpler and more accurate than the plastic limit, so in some areas with experiences, the liquid limit is tested so as to convert it to the plastic limit, that is, there are some relationships between the plastic limit of soil and its liquid limit. Therefore, for the soil with same water content, its liquid limit largely determines the plasticity index and liquidity index of the soil. The liquidity index and plasticity index are the main physical property indexes of the soil, which are closely related to the mechanical properties of the soil. Therefore, the liquid limit of clayey soil has a significant impact on the engineering properties of soil.

2. Influence of liquid limit on the classification and denomination of soil

According to soil mechanics or relevant standards such as “Specification for Geotechnical Investigation of Marine Traffic Engineering” (JTS133-2013) [3] [4], fine-grained soil can be divided into silt and clayey soil according to particle composition and plasticity index, and clayey soil can be divided into silty clay and clay. Clayey soil deposited in still water or slow flowing water environment, with natural water content greater than or equal to 36% and greater than liquid limit, and natural void ration greater than or equal to 1.0 shall be named as silt soil. Silt soil can be further divided into mucky soil, sludge and quick mud, and mucky soil can be divided into mucky silty clay and mucky clay according to plasticity index Ip.

| Classification and denomination | Silt | Silty clay | Clay |
|---------------------------------|------|------------|------|
| Plasticity index Ip             | Ip≤10| 10< Ip≤17  | Ip>17|

Note: fine-grained soil refers to that the mass of soil with particle size less than 0.075mm exceeds 50% of the total mass.

Table 2. Classification and denomination of silt soil

|                  | Mucky silty clay | Mucky clay | Sludge | Quick mud |
|------------------|------------------|------------|--------|-----------|
| Void ratio e     | 1.0≤e<1.5, 10< Ip≤17 | 1.0≤e<1.5, Ip>17 | 1.5≤e<2.4 | e≥2.4     |
| Water content w/% | wL<36≤w<55     | wL<36≤w<55     | wL<55≤w<85 | w≥85      |

Table 1 and Table 2 are listed according to the classification and denomination of soil, and the concept of various types of soil is clear and rigorous. It is not difficult to find that the division of silt and clayey soil is only related to the particle composition and plasticity index of soil, that is to say, it is related to the liquid limit but not related to the soil state of water content, void ratio, density, etc., which is the self-property of fine-grained soil. The definition of silt soil is different, which is related to the depositional conditions, water content, liquid limit and void ratio. It is the further denomination of clayey soil in a certain state. Even if the water content is high and the void ratio is large, as long as the water content does not exceed the liquid limit, it cannot be named silt soil. This phenomenon is often encountered in practical engineering. The liquid limit of soil is very important for its classification and denomination, and its value directly affects the denomination of soil.

3. Influence of liquid limit on mechanical properties of soil

Relying on the basic scientific research operating fee project of the central public welfare research institute and the foundation testing project of Xuwei New District, Lianyungang City, Jiangsu Province, the project team conducted drilling sampling, field in-situ test and geotechnical test in the south section of Xuwei Town, Xuwei New District, Lianyungang City, Jiangsu Province from November to December 2017.

The test depth of drilling sampling and in-situ test is 18m below the original ground, and the elevation of the original ground is about + 3.5m, with 30 drilling sampling holes, 30 vane test holes and 30
standard penetration test holes. The sampling and in-situ test are carried out along the depth with the interval of 1 meter. Drilling reveals that within the depth of 18m in this test section, clay, mucky soil and sludge are the main soil types, and silty clay is found in some of the drilling holes. The saturation Sr of all soil layers is more than 97%, which is saturated soil with relatively uniform soil layer, belonging to littoral sediment landform. The physical property parameters of selected representative soil samples are shown in Table 3.

| Soil sample No. | Depth of soil collection /m | Water content w/% | Density ρ/g/cm³ | Void ratio e | Liquid limit wL/% | Plastic limit wP/% | Plasticity index IP | Liquidity index IL | Classification of soil |
|-----------------|---------------------------|------------------|----------------|-------------|------------------|------------------|-------------------|-------------------|-----------------------|
| 1               | 0.8                       | 36.1             | 1.86           | 1.005       | 31.5             | 18.6             | 1.36              | mucky silty clay    |
| 2               | 1.8                       | 37.9             | 1.85           | 1.042       | 44.2             | 21.4             | 0.72              | clay               |
| 3               | 4.8                       | 50.2             | 1.72           | 1.393       | 54.6             | 24.4             | 0.85              | clay               |
| 4               | 5.8                       | 57.3             | 1.66           | 1.596       | 57.5             | 25.3             | 0.99              | clay               |
| 5               | 9.8                       | 49.1             | 1.74           | 1.348       | 49.0             | 22.8             | 1.00              | mucky clay         |
| 6               | 10.8                      | 53.6             | 1.70           | 1.476       | 52.8             | 23.9             | 1.03              | mucky clay         |
| 7               | 11.8                      | 56.2             | 1.67           | 1.563       | 57.2             | 25.2             | 0.97              | clay               |
| 8               | 12.8                      | 62.4             | 1.64           | 1.713       | 52.5             | 23.8             | 1.34              | sludge             |
| 9               | 16.8                      | 57.6             | 1.66           | 1.601       | 56.3             | 24.9             | 31.4              | sludge             |
| 10              | 17.8                      | 55.0             | 1.68           | 1.528       | 56.7             | 25.0             | 0.95              | clay               |

It can be seen from Table 3 that the liquid limit of soil sample is relatively high. When the liquid limit WL ≥ 50%, it can be called high liquid limit soil. From the two indexes of water content and void ratio, 10 groups of soil samples should be sludge or mucky soil. However, because the water content is less than the liquid limit, soil samples No. 1, 2, 3, 4, 7 and 10 cannot be named mucky soil. The water content of these groups of clay is as high as 57.3%, and the void ratio is about 1.596, which are far greater than 55% and 1.5 respectively. Many people think that soil samples with such a large water content and void ratio should be sludge, but actually it is not. Soil samples No. 5, 6 and 9 are mucky clay and sludge, and their water content is also close to the liquid limit. Otherwise, there will be another denomination. The test of water content is relatively simple and not easy to make mistakes, so the accuracy of the test of liquid limit is very important.

3.1. The state and natural state of clayey soil

According to Table 3, soil samples No. 1 and No. 8 have a liquid index greater than 1, which are flow plastic. Other soil samples have a liquid index less than or close to 1, which are in a soft plastic state. Soil sample No. 2 even reaches a plastic state. Although the water content is very high, due to the high liquid limit, the soil is still relatively hard, and there is no flow plastic or shapeless slurry state. On the contrary, the water content of soil sample No. 1 is relatively low, but its state is flow plastic, which is very soft. When the soil sample is opened, it cannot even stand on the table. It is the sludge soil sample with the liquid index greater than 8 and 9.

It can be concluded that even if the water content of soil is very high, as long as the liquid limit is large enough, the soil will still be relatively hard. If the water content of soil is relatively low, even about 35%, due to the low liquid limit and high liquid index, the soil will also be very soft.

The soft and hard state of the undisturbed soil sample taken from the site can be expressed by the cone sinking amount h, i.e. the depth that the 76g cone meter sinks into the soil. In this experiment, the undisturbed soil sample is cut into soil blocks with side length of 5cm and thickness of about 3 ~ 5cm. When the estimated value of cone sinking amount is small, the circular soil sample directly cut by the ring cutter can also be used. After the sample is made, it is placed on the lifting seat of the joint tester of liquid & plastic limit. The cone mass is 76g, and the cone angle is 30°. The cone tip is coated with a thin layer of Vaseline. The joint tester of liquid & plastic limit is connected with the power supply to make the electromagnet hold the cone. Adjust the zero point by adjusting the scale on the screen to the zero
position, and adjust the lifting seat to make the cone tip contact the sample surface. When the indicator light is on, the cone will sink into the sample under the action of dead weight. Five seconds later, measure and read the cone sinking depth $h$, that is, the cone sinking amount, then repeat the above steps. One sample can be sunk twice, and the average cone sinking amount is obtained. See Table 4 for sample results.

| Soil sample No. | 1   | 2   | 3   | 4   | 5   | 6   | 7   | 8   | 9   | 10  |
|-----------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Cone sinking amount $h$/mm | 8.5 | 2.7 | 3.9 | 4.9 | 4.5 | 4.8 | 4.7 | 6.3 | 5.0 | 3.9 |
| Natural state   | very soft | hard | medium | medium | medium | medium | medium | soft | soft | medium |

The cone sinking amount $h$ of each soil sample is obtained through the test. According to the “Specification for Geotechnical Investigation of Marine Traffic Engineering” (JTS 133-2013), the natural state of each soil sample can be determined, as shown in Table 4. Among them, the natural state of soil No. 1 is very soft, and its cone sinking amount is 8.5mm, which is much larger than that of sludge No. 8 and No. 9. The cone sinking amount of other soil samples is mostly less than 5mm, and the natural state is medium or even hard.

It can be concluded that even if the natural water content of soil is very high, as long as the liquid limit is large enough, its natural state will still be relatively hard. If the water content of soil is relatively low, even about 35%, due to the low liquid limit, its natural state will also be very soft.

Using liquidity index to judge the state of clayey soil refers to the soft and hard degree of soil sample under a certain water content condition, without considering the disturbance of soil and the structure of soil. Judging the natural state of clayey soil according to the cone sinking amount obviously refers to the soft and hard degree of undisturbed soil, taking into account the structure of soil.

3.2. Influence of liquid limit on strength and bearing capacity of clayey soil

In order to test the strength and bearing capacity of the foundation soil in the test section, 30 sets of vane test and 30 sets of standard penetration test (SPT) are carried out on site. The results of vane test and standard penetration test at representative in-situ test points are shown in Figure 1 and Figure 2.

![Figure 1. The curve of vane shear strength with test depth](image-url)
It can be seen from Figure 1 that the liquid limit and the undrained shear strength of the surface mucky silty clay are lower than that of the rest soil layers. The undrained shear strength of the rest soil layers is between 35-50kPa. It is common that the undrained shear strength of the general clayey soil reaches or exceeds this value, but people often ignore this kind of clayey soil with high water content, even the sludge and mucky soil having such high shear strength. According to the collected data of littoral sediment clayey soil in Binhai New Area of Tianjin, Huanghua of Hebei, Binzhou of Shandong and other Bohai Bay areas, the clayey soil with water content of 50% ~ 70%, whose liquid limit is relatively low compared with the soil sample in this test section, has the vane shear strength generally in the range of 5 ~ 30 kPa in the 20 m depth.

It can be seen from Figure 2 that the SPT blow count of each soil layer is 3 ~ 6, which is relatively high. The SPT data of littoral sediment clayey soil in other areas of Bohai Bay show that the blow counts of clayey soil with water content of 50% ~ 70% and low liquid limit are basically 0 ~ 2, most of which are self-dropping.

The bearing capacity of the foundation soil can be calculated according to the vane shear strength, i.e. \( q = 2c_u + \rho h \), where \( c_u \) is the modified vane shear strength, which can be taken as 36kPa; \( \rho \) is the unit weight of the soil, which can be taken as 17kN/m3; \( h \) is the buried depth of the foundation, which can be taken as 2m for calculation. The bearing capacity of foundation is obtained as \( q = 106 \) kPa.

The bearing capacity of the foundation soil can also be obtained by looking up the table according to the SPT blow count and the physical properties of the soil layer. When checking the table according to the liquidity index and the void ratio of the clayey soil, only the data when the void ratio \( e \leq 1.2 \) can be found in the table. If \( e = 1.2 \) is taken, the bearing capacity of the foundation is about 100 kPa. The bearing capacity of the foundation of the main soil layer is shown in Table 5.

| Look-up method | SPT blow count | Natural water content | Liquidity index and void ratio | Vane shear strength |
|----------------|----------------|-----------------------|-------------------------------|--------------------|
| Parameter value | N'=3~4         | w=50%~65%             | IL=0.7~1.0,e=1.2              | cu=36 kPa          |
| Bearing capacity eigenvalue f/kPa | 105           | 60                    | 100                           | 106                |

It can be seen from Table 5 that the estimated bearing capacity of the foundation is about 105 kPa based on the in-situ test results, and the bearing capacity is 100 kPa based on the liquidity index and void ratio, which is close to the in-situ test results. However, the bearing capacity based on the natural water content is about 60 kPa, which is 40% lower. Because when looking up the table according to the
natural water content, the influence of liquidity index is not considered, that is, the influence of liquid limit is not considered.

It can be seen that the liquid limit has a great influence on the strength and bearing capacity of clayey soil, which cannot be ignored. For clayey soil with high water content, the strength and bearing capacity of high liquid limit soil can be increased by more than 40% compared with low liquid limit soil.

3.3. Analysis of the influence of liquid limit on the deformation parameters of clayey soil

The e-P curve of the consolidation test of 10 groups of soil samples in the test section is shown in Figure 3, and the test method is in accordance with the “Standard for Soil Test Method” (GB / T 50123-1999) [5].

![Figure 3. e-P curve of 10 groups of soil samples](image)

According to the e-P curve, the coefficient of compressibility and modulus of compressibility at all levels of pressure can be calculated. Here, only the coefficient of compressibility and modulus of compressibility at the pressure of 100 ~ 200 kPa are calculated. See Table 6 for the calculation results.

| Soil sample No. | 1    | 2    | 3    | 4    | 5    | 6    | 7    | 8    | 9    | 10   |
|-----------------|------|------|------|------|------|------|------|------|------|------|
| Coefficient of compressibility av/ MPa<sup>-1</sup> | 0.59 | 0.62 | 0.96 | 1.17 | 1.04 | 1.06 | 1.29 | 1.35 | 1.20 | 1.12 |
| Modulus of compressibility Es/MPa            | 3.40 | 3.29 | 2.49 | 2.22 | 2.26 | 2.34 | 1.99 | 2.01 | 2.17 | 2.26 |

It can be seen from Figure 3 and Table 6 that the water content and void ration of soil samples No. 1 and No. 2 are relatively close, and the difference of liquid limit is large, but the difference between their coefficient of compressibility and modulus of compressibility is not big, while the coefficient of compressibility of other soil samples is far greater than that of soil samples No. 1 and No. 2, and the modulus of compressibility is also small. It can be concluded that, although it is clay, its coefficient of compressibility and modulus of compressibility are similar to those of silt soil. Although soil sample
No. 1 is silt soil, its coefficient of compressibility is relatively low, and its modulus of compressibility is relatively high. The liquid limit has little effect on the coefficient of compressibility and modulus of compressibility, which are mainly affected by water content and void ratio.

According to the relationship between deformation and time under a certain level of pressure, the corresponding consolidation coefficient can be calculated by time square root method, as shown in Table 7.

| Soil sample No. | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|-----------------|---|---|---|---|---|---|---|---|---|----|
| Consolidation coefficient Cv/10^{-3}cm^{2}/s | 5.4 | 0.82 | 0.42 | 0.21 | 0.76 | 0.63 | 0.36 | 0.78 | 0.51 | 0.45 |

It can be seen from Table 7 that the consolidation coefficient of soil sample No. 1 is 5.4×10^{-3} cm^{2}/s, which is far greater than that of other nine soil samples. The liquid limit of soil sample No.1 is far less than that of other soil samples, indicating that the liquid limit of soil affects the consolidation coefficient. The larger the liquid limit is, the finer the particle composition is, the more the clay particles are [6], and generally the smaller the permeability coefficient is, so the consolidation coefficient is also smaller. The consolidation coefficient is mainly related to the permeability coefficient, void ratio and coefficient of compressibility of soil. When using the time square root method, the consolidation coefficient is only related to the drainage distance and consolidation time. The large consolidation coefficient of soil sample No.1 means that its consolidation time is small. The liquid limit has a great influence on the engineering properties of soil.

4. Conclusion

(1) This paper expounds the importance of the liquid limit of soil. The classification of silt and clayey soil is only related to the particle composition and plasticity index of soil. The further classification and denomination of clay is directly affected by the liquid limit. Even if the water content is high and the void ratio is large, as long as the water content does not exceed the liquid limit, it cannot be named as silt soil.

(2) The liquid limit and cone sinking amount are used to judge the state and natural state of clayey soil. When the water content is the same, the higher the liquid limit is, the harder the soil will be. The conclusion is further illustrated by using the cone sinking amount at the same time.

(3) The influence of liquid limit on the strength and bearing capacity of clayey soil cannot be ignored. For clayey soil with high water content, the undrained shear strength and bearing capacity of high liquid limit soil can be increased by more than 40% compared with low liquid limit soil.

(4) The influence of liquid limit is small on the coefficient of compressibility and modulus of compressibility, but large on the consolidation coefficient. In general, the larger the liquid limit is, the smaller the consolidation coefficient is.

Acknowledgments

Fund projects: Central level public welfare research institutes basic research operating expenses (TKS170225; TKS180407)

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