Experimental study on consolidation characteristics of collapsing soil under different dry densities

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Abstract. The occurrence and development of collapsed hills in southern China are significantly affected by soil properties and consolidation characteristics. Three different dry densities were set up in the study. The four-layer soil was subjected to indoor one-dimensional consolidation test, in order to study the consolidation characteristics. The results show that the soil consolidation properties of different layers are different under different dry densities. Under the same load pressure, the four-layer soil’s pore ratio decrease with the increase of dry density; no matter how the dry density changes, the topsoil has a minimum pore ratio as the load increases. The maximum relative deformation rate occurs at the load pressure is 200 Kpa, the overall trend is the inverted “v” trend; the trend of compression coefficient of every treated soil sample is the same as the compression index, and the maximum value is the topsoil when the dry density is 1.40g/cm³. 1.40 g/cm³ of topsoil is high compressive soil, most of the rest are medium and low compressive soil. In this paper, from the consolidation characteristics of each soil layers under different dry densities reveal the mechanism of collapsing, which provides scientific basis for the prevention and control of collapse.

1. Introduction
Collapsing erosion is called “ecological ulcer” in China's soil and water conservation work (Wei et al., 2016), which occurs mostly in Fujian and Guangdong, and is located in the red soil with relatively low latitude in the tropical and subtropical regions, is a special type of gully erosion. The area of benggang in China is about 1200km², and its erosion modulus is huge, reaching an average of 3~1.5×10⁵ t/km²·a (Liang et al., 2009), far exceeding the allowable loss rate of soil standard values in southern China (500t/km²). The speed of erosion is very fast, with sudden and long-term characteristics.

For the formation mechanism of collapsed posts, different scholars have different views on the hydraulic, gravity and various factors of the category of collapse. The instability of the collapsed slope is related to the granite that has been expanded by weathering (Zhang et al.,2005). The development and evolution process of the collapsed hill is closely related to the mechanical properties of the rock (Jiang et al.,2013). It will lead to uneven settlement of collapsing soil, which leads to collapse and engineering damage(Zhang et al.,2016). As the number of dry and wet cycles increases, especially after the second cycle, the main fractures occur in the rock and soil(Liu et al.,2016). The crack ratio is significantly increased, and the disintegration is on the rise.
In view of the special geotechnical characteristics of the collapsed area, it is necessary to take corresponding measures to control it. The consolidation characteristics of geotechnical properties are an important part of soil mechanics research. This study is mainly to study the consolidation characteristics of soils at different levels of dry density, change the dry density of soil and increase the consolidation characteristics, so to a certain extent to improve soil stability and reduce erosion.

2. Materials and methods

2.1 Overview of the study area
The study area is located in Tongcheng County, Xianning City, Hubei Province. The county has abundant rainfall, with an average annual precipitation of more than 1000mm. Gale, hail, drought and flood are the main types of disasters. The vegetation coverage is only 35%. The granite in this area is severely weathered, the weathering crust is loose, and the soil structure is loose, which leads to serious erosion of the collapsed land. The distribution reaches half of the national total and the concentration is high. It is listed as a national key county for collapse prevention and control. Among them, the erosion of the collapsed hills in Wuli Town is relatively concentrated and the degree is serious. It can be seen that choosing this area as studying area has certain reliability and representativeness.

2.2 Stratification and sampling
The sampling point is set in Wuli Community, Tongcheng, Hubei Province. The geographical position is roughly at 113°E, 29°N, and the altitude is 142m. Red-brown soil is found throughout the area. By observing the degree of granite development in the sampling area, the soil profile is divided from top to bottom according to soil color and texture according to different depths (0.3, 4.0, 8.0, 9.0m), including topsoil, red soil, striation and debris. The basic properties of each soil layer are described in Table 1. The samples were taken as undisturbed soil and loose soil. Using the ring cutter (61.8mm × 20mm) was inserted into the vertical section of soil to take the undisturbed soil and quickly placed in an uncontaminated plastic bag for storage, sampling method adopts mixed sampling and S-type sampling. Representative loose soil samples of about 1kg were taken from the most typical part of each layer, labeled, carefully recorded and brought back to the laboratory for use.

| Soil layer | Sampling depth(m) | Description the characteristic of soil layer |
|------------|------------------|-------------------------------------------|
| topsoil    | 0.0-0.3          | The soil is dark red, the roots are visible to the naked eye, the surface is sparsely vegetated, and it has a good structure; the texture of the soil is fine. |
| red soil   | 0.8-4.0          | The soil is red, the root system is less distributed, and the structure is firm. The color of the soil is light red to grayish white, there is no plant root system, the structure is relatively loose, the particle size is obviously increased, and the sandy texture is strong. |
| striation  | 5.5-8.0          | The color of the soil is grayish white, the structure is loose, the particle size continues to increase, and the large particles have a strong sandy texture. |

2.3 Test methods
After the loose soil is air-dried and crushed into a 2 mm sieve, and a part of the sieved soil is sealed and bagged, and measuring the natural moisture content, bulk density, texture, and boundary moisture content (the natural moisture content and the bulk density are measured by drying and weighing); The texture adopts the sieve analysis method combined with the pipette method, and the boundary moisture content is determined by the liquid-plastic limit combined method); the other part is dried by the oven constant temperature at 105°C until it is completely dried, and the reshaped soil sample is prepared by the compaction method. The moisture content of each layer was controlled to 20%, and
three dry density indexes were set: 1.35 g/cm$^3$, 1.40 g/cm$^3$, and 1.45 g/cm$^3$. 3 dry density × 3 replicates × 4 layers of soil = 36 samples were tested. The fast consolidation experiment was carried out using a WG-type single-lever consolidation instrument (shown in Figure 1) with the load pressure set to 12.5, 25, 50, 100, 200, 300, 400 Kpa. During the experiment, the deformation of the specimen under each load, the reading of the consolidation gauge at 1h, and the change in the steady state under 400 Kpa load were recorded. Calculate the relative change rate of the sample height (see Equation 1).

$$\Delta H_{i+1} = \frac{Z_{i+1} - Z_i}{H_0} \times 100\%$$

$\Delta h_{i+1}$ is the relative deformation rate (%) under the consolidation pressure of $i+1$; $Z_i$, $Z_{i+1}$ refers to the specific reading (mm) of the dialect under the two adjacent consolidation pressures; $h_0$ is the initial height (mm) of the sample.

3. Results and analysis

3.1 Basic properties of soil samples

The basic physical properties of each soil layer are shown in Table 2. The particle size distribution of the four soil layers is relatively balanced. The clay content from the topsoil layer to the striation layer is gradually increased, and the striated layer is the largest. The higher the clay content, the stronger the water holding performance. The plasticity index is a criterion for judging the water absorption capacity of the soil. The debris layer has the smallest plasticity index and the water absorption capacity is the worst. In this way, it is easy to form a water-repellent layer between the striated layer and the debris layer, and so that it is easy to collapsing.

| Soil layer  | Moisture content (%) | Bulk weight (g/cm$^3$) | Dry density (g/cm$^3$) | Plasticity index | Soil mechanical composition |
|-------------|----------------------|------------------------|------------------------|------------------|-----------------------------|
|             |                      |                        |                        |                  | Clay (%) Powder (%) Sand (%)|
| topsoil     | 19.5                 | 1.37                   | 1.38                   | 24.71            | 34.42 24.93 39.45           |
| red soil    | 21.0                 | 1.36                   | 1.35                   | 26.63            | 36.06 25.47 37.77           |
| striation   | 22.7                 | 1.39                   | 1.39                   | 20.2             | 42.28 23.85 33.85           |
| debris      | 23.3                 | 1.44                   | 1.41                   | 11.98            | 16.10 29.55 53.95           |

3.2 Consolidation characteristics of various soil layers under different dry densities

3.2.1 Changes of soil pore ratio during compression
Fig. 2(a)-(d) are respectively the curves of pore ratio with the load for the same layer of soil at three dry densities. It can be seen that except for the striation layer, the other three soil layers presenting the trend of decreasing first and then increasing is “V” type as the applied load increasing, and the lowest value is at 200 Kpa. Therefore, when the load pressure is 200Kpa, the pore ratio of the soil is the smallest and the consolidation characteristics are the strongest. Among them, the pore ratio of the topsoil and the debris layer at 400 Kpa is smaller than the initial value, and the compaction is general. Under the same load, the pore ratio of four layers decreases with the increase of dry density. Therefore, the higher the dry density, the stronger the consolidation characteristics.

![Fig. 2](image2.png)

Fig. 3(e)-(g) are respectively the curves of the pore ratio of the four layers with the load at the same dry density. It can be seen that at the dry density of 1.35g/cm³ and 1.40g/cm³, the pore ratio is the striation layer >the red soil layer >the debris layer >the topsoil layer. When the dry density is 1.45 g/cm³, it is the striated layer>the debris layer> the red soil layer> the topsoil layer. It shows that the topsoil layer has the best consolidation characteristics in the four layers of soil. The treatment of dry density 1.40 g/cm³ in the red soil layer at 200 Kpa, the pore ratio suddenly increases, which may be due to the large amount of micro-cracks emerging in the soil during the compression process.

![Fig. 3](image3.png)
Fig. 3 the $e - p$ curve in the compression process

3.2.2 Change of relative deformation rate of soil during compression

Figures 4(h)-(j) are respectively representing the relative deformation rate of four layers soil with the load increasing at the same dry density. It can be seen that with the increase of load, the relative deformation rate of each soil layer increases first and then decreases, and its value is roughly distributed in the range of 1%~8%, the lowest value is basically at 25 Kpa load pressure; then continue to rise until the 200 Kpa load pressure reaches a peak value of nearly 8%. When it is greater than 200kpa, the relative deformation rate begins to decrease with the increase of the load, and when the dry density is 1.45 g/cm$^3$ and the topsoil layer is the most typical. Generally, the relative deformation rate increases with the increase of externally applied load, but in this study the lowest value at 25kpa may be caused by human error, or the instrument is placed unbalanced, and the soil pressure is transferred. When the pressure is continuously applied 200Kpa, the relative deformation rate of each soil layer shows a significant downward trend, which is due to the limit of soil stress.
3.2.3 Consolidation index

Through the data processing recorded by the consolidation test, three qualitative indexes of compression coefficient, compression index and compression modulus were calculated to evaluate the degree of compression and consolidation of the soil.

The compression coefficient of each soil sample treatment ranged from -0.07MPa \(^{-1}\) to 0.708MPa \(^{-1}\), the maximum value of the compression coefficient appeared in the dry density of 1.40 g/cm\(^3\) in the topsoil, and the minimum value also appeared in this layer with a dry density of 1.35 g/cm\(^3\). In the same soil layer, the general rule of the compression coefficient of the striation layer and the debris layer is that the value increases with the increase of the dry density. In the treated soil layer with a dry density of 1.35 g/cm\(^3\), except for the red soil layer, the compressibility and compression index of other soil layers are smaller, indicating that the red soil layer sample under the dry density has good compressibility and the degree reduction of pore ratio will improve. The project stipulates that when the compression coefficient \(\geq 0.5\)MPa\(^{-1}\), it is a highly compressed soil. Therefore, the sample with a dry density of 1.40 g/cm\(^3\) in the topsoil is a high compressibility soil, and most of the remaining are medium and low compressive soils.

![Fig.4 Relative deformation rate of soil during compression](image)

| Treated soil sample | Compression factor \(a_v (\text{MPa}^{-1})\) | Compression index \(C'_c\) | Compression modulus \(C'_c (\text{MPa}^{-1})\) |
|--------------------|---------------------------------|-----------------|-----------------|
| 1-1                | 0.0697±0.023cdef                | 0.023±0.008cdef | 25.483±8.398a   |
| 1-2                | 0.708±0.0735a                   | 0.236±0.025a    | 2.189±0.241b    |
| 1-3                | 0.403±0.040abcd                 | 0.134±0.014abcd | 3.704±0.355b    |
| 2-1                | 0.321±0.043abcde                | 0.107±0.014abcde| 5.157±0.648b    |
| 2-2                | 0.043±0.624def                  | 0.011±0.207def  | 2.532±4.811b    |

Table 3. Consolidation Index value of soil samples with different treatments
The compression index of each soil sample varies from -0.023 to 0.236, and its theory is consistent with the compression coefficient. The larger the value, the higher the compressibility. The largest compression index is a sample with a dry density of 1.40 g/cm³ in the topsoil, which is basically the same as the compression coefficient. In the same soil layer, there is no obvious discipline for the same soil layers with different dry densities.

The compressive modulus is determined by the combination of the compression coefficient and the initial pore ratio. The compression modulus is inversely proportional to the compression coefficient and is proportional to the initial pore ratio. The larger the compression modulus, the worse the soil consolidation characteristics. The topsoil and red soil layers have the largest compressive modulus at a dry density of 1.35 g/cm³. Therefore, when the dry density of soil in the natural world is about 1.35 g/cm³, it is easily damaged by external forces to some extent, which leads to the development of benggang. At present, the research can not effectively reflect the consolidation mechanical properties of different structures in the collapsed soil in nature. It can only be understood that the dry density is between 1.35g/cm³ and 1.45g/cm³, especially in the vicinity of 1.40g/cm³, the difference in consolidation characteristics varies greatly. If we want a good effect difference, and it is necessary to carry out a large number of related tests.

4. Conclusion and analysis

Through the analysis of the preliminary basic properties of the four layers of soil in the collapsed soil erosion zone, and then the different dry density treatments, the indoor one-dimensional rapid consolidation test, and the following conclusions are drawn:

(1) In the eroded area, the basic properties of the soil layers are different. The natural water content is the topsoil layer < the red soil layer < the striate layer < the debris layer, and the soil bulk density is the red soil layer < the topsoil layer < the striate layer < the debris layer. The soil layer density of the red soil layer is the largest, 2.65 g/cm³, and the value of the topsoil layer is the smallest. The plasticity index decreases from the red soil layer to the debris layer, indicating that the debris layer is most easily compressed and deformed after being subjected to external pressure, resulting in soil loss. The topsoil is affected by leaching and precipitation, resulting in increased clay content in the lower soil, and the highest appeared in the striation layer. The sand content was the highest in the debris layer.

(2) The soil consolidation properties of different layers are different under different dry densities. Under the same load, the pore ratio of four layers soil decreases with the increase of dry density. Therefore, the higher the dry density, the stronger the consolidation characteristics; no matter how the dry density changes, the pore ratio of the topsoil layer is the smallest with the increase of load, so the topsoil has the strongest Consolidation characteristics in the four layers of soil. When the relative deformation rate maximum occurs at 200 Kpa, and the overall is an inverted "V" trend.

(3) The each treated soil sample’s changing trend of compression coefficient is the same as the compression index. The maximum value is 1.40 g/cm³ dry density of the topsoil layer, which has good compressibility, large reduction of pore ratio and strongest consolidation characteristics. When the dry density is 1.35 g/cm³, the topsoil and the red soil layer have the largest compressive modulus and poor consolidation characteristics. In the consolidation performance, the topsoil layer 1.40 g/cm³ is a highly compressive soil, and most of the remaining is a medium-low compressive soil, and the compression index tends to be substantially the same.
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