J. Zhang et al.: Diametric splitting tests on unsaturated expansive soil with different dry densities based on the particle-image-velocimetry technique

DIAMETRIC SPLITTING TESTS ON UNSATURATED EXPANSIVE SOIL WITH DIFFERENT DRY DENSITIES BASED ON PARTICLE IMAGE VELOCIMETRY TECHNIQUE

Izvleček
Med nateznim naporom in nateznim napetostim, sosednjimi deformacijami v celotnem procesu porušitve redko preučujejo, ker obstajajo dvomi v natančnost merjenja strižnih specifičnih deformacij s tradicionalnimi metodami. V tem prispevku smo uporabili novo razvit diametralno cepilno preskusno napravo in optično metodo delec-slika-meritev hitrosti (PIV) za preučevanje nateznih trdnosti in različnih začetnih suhih gostot. Krivulje zemljin-voda za trdne ekspanzivne zemlje z različnimi začetnimi suhimi gostotami so bile določene z metodo filtriranega papirja. Rezultati preizkusov kažejo, da se nate-

Keywords
Diametric splitting, tensile strength, unsaturated expansive soil, particle image velocimetry

Abstract
There is a close relationship between tensile strength of soil and crack development, but the tensile stress-strain in full failure process is rarely studied because challenges exist in accurately measuring shear strain using traditional methods. In this paper, we employed a newly developed diametric splitting testing apparatus and particle image velocimetry (PIV) system to study the tensile strength of compacted unsaturated expansive soil with different water contents and initial dry densities. Soil water characteristic curves of compacted expansive soil with different initial dry densities were determined using the filter paper method. Test results show that the tensile strength increases first and then decreases with increasing water content,

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Ključne besede
Diametralni cepitev, natezna trdnost, nenasičena ekspanzivna zemljinija, optična metode delec-slika-meritev hitrosti (PIV)

Izvleček
Med natezno trdnostjo zemljin in nastankom razpok obstaja tesna povezava, vendar se odnos med nateznimi napetostmi in specifičnimi deformacijami v celotnem procesu porušitve redko preučujejo, ker obstajajo dvomi v natančnost merjenja strižnih specifičnih deformacij s tradicionalnimi metodami. V tem prispevku smo uporabili novo razvit diametralno cepilno preskusno napravo in optično metodo delec-slika-meritev hitrosti (PIV) za preučevanje nateznih trdnosti trdne, nenasičene ekspanzivne zemljinije z različno vlaznostjo in začetno suho gostoto. Krivulje zemljin-voda za trdne ekspanzivne zemlje z različnimi začetnimi suhimi gostotami so bile določene z metodo filtriranega papirja. Rezultati preizkusov kažejo, da se nate-
and there is a critical water content for the peak load vs. water content curve. The diametric splitting test process can be divided into four stages on the basis of the plotted load-displacement curves: a stress contact adjustment stage (I); stress approximately linear increasing stage (II); tensile failure stage (III); and residual stage (IV). Under the same water content, the angle between the major directions of the displacement vector and the major crack decreases with increasing the dry density, especially when the fissure appears. Using the particle image velocimetry technique, the displacement and strain during the test process recorded is helpful for better understanding the soil failure mechanism.

1 INTRODUCTION

Tensile strength is an important soil-strength parameter to describe the soil’s resistance to loading, and is considerably smaller than other aspects of soil strength [47]. Expansive soil is a typical special soil, which has the characteristics of expansion, contraction, fissuring, and over-consolidation, owing to its hydrophilic minerals, such as montmorillonite. Expansive soils are particularly sensitive to climate changes. As shown in Ng et al. [25], the hydro-mechanical behavior of expansive soils was significantly affected by climate changes, which can lead to a severe disaster for geotechnical engineering. Desiccation cracking is a common phenomenon during the drying and wetting cycles for expansive soils that occur in various geotechnical engineering projects, such as dams, slopes and embankments [5], [35], [38]. Previous studies have shown that the cracks change remarkably through the hydro-mechanical behavior of soils [41]. Cracks in the soils lead to a sharp increase in the permeability coefficient. At the same time, the existence of cracks will aggravate the corrosion of soils and leads to an increase in the probability of geological disaster [33], [36].

Extreme drought has occurred in recent years, with increasing frequency and soil desiccation cracking [42], [34], [14]. Desiccation cracking occurs when the tensile stress in the soil exceeds a certain limit (i.e., tensile strength) [23]. Determination of the soil-cracking mechanism and improving the safety of geotechnical structures are therefore of great significance to comprehensively understand the tensile strength of special soils, especially for expansive soil.

The testing methods for measuring soil’s tensile strength include direct and indirect methods. The indirect tensile-test methods include the split tensile test, the beam bending test and the axial fracturing test [7], [37], [12], [18], [24], [22], [6]. The above methods are suitable for rock and concrete. For soft soils, some coefficients are necessary [7] to correct the test results.

Most previous studies used a linear variable differential transducer (LVDT) to measure the deformation of the specimens with regard to the tensile strain. The LVDT method is suitable for uniform soils. The development of image-processing techniques in recent decades has significantly improved strain measurements. The displacement and strain on the specimen’s surface can be tracking in a full process by using the particle-image-velocimetry (PIV) and digital-image-correlation (DIC) techniques [46], [11], [1]. The PIV technique has the advantages of non-contact and high resolution, and it has been widely applied in geotechnical engineering [45], [5], [19], [31], [44], [43], [49]. These studies reported that desiccation crack sites can be reliably predicted on the basis of the surface strain field.

Many researches have focused on the tensile strength of unsaturated soil (e.g., [20], [21], [13], [4], [38], [40], [17], [47], [8], in which most studies are mainly focused on the tensile strength. However, the tensile stress-strain in a full-failure process is rarely studied, and because of that there are challenges in accurately measuring the shear strain using traditional methods. Moreover, the influence of the initial dry density and the water content on the tensile stress of expansive soil during the tensile-test process and the failure mechanism remain unclear. It needs further study [16].

In order to study the tensile stress-strain in the full-failure process of expansive soil systematically, we have designed a new diametric splitting test with a PIV system. The DIC and PIV techniques were employed to obtain the strain field. A series of diametric splitting tests were conducted on compacted, unsaturated, expansive soil specimens with different water contents.
of 10–22 % and initial dry densities of 1.35–1.65 Mg/m³. The test results are analyzed and discussed in the following, together with the PIV images.

2 MATERIAL AND METHODS

2.1 Testing apparatus

The diametric splitting testing apparatus with the PIV system is shown in Figure 1. The diametric splitting testing apparatus consists of three systems: the loading test system, the data collection system, and the PIV system. During the test, the three systems were synchronized. The loading system used in the tests is the CMT4000 electronic universal testing machine developed by the American Meester Company. This instrument includes the loading equipment and the data-acquisition system and can automatically control the constant-velocity displacement rate. The load is applied using the strain control type with the compression rate ranging from 0 to 10 mm per minute. The speed selected in this study is 1.4 mm per minute. The data of the load is monitored using a load cell with a maximum range of 160 N, and a working resolution of 0.001 N. During the test, the displacement and load measurements are carried out simultaneously. The displacement is monitored by a LVDT with a maximum range of 100 mm and a working resolution of 0.001 mm.

A high-speed CCD camera with high sensitivity and image quality was vertically mounted above the specimen and manually focused on the specimen’s surface. Seven pictures were taken per second to record the deformation in the full process. Davis8.3 software was then used to obtain the required images and specific locations were selected and analyzed using PIVview2C and Tecplot10 instruments. The size range of the specimens photographed in the tests is about 38.5 × 38.5 cm². The initial specimen size used in the tests is $d_0 = 6.18$ cm and $h_0 = 2$ cm.

2.2 Soil sample

The expansive soil was collected from Nanyang City, Henan Province, China, and is similar to that used in Zhang et al. [48] but from a different location. The expansive soil has a liquid limit of 52.7 % and a plasticity index of 29 %. Other physical property indexes, such as specific gravity, liquid limit, plastic limit, optimum water content, maximum dry density, and free swelling ratio, are listed in Table 1.

![Grading curve of the expansive soil.](image)

Fig. 2 shows the grading curve determined by the hydrometer analyses. The soil is composed of 21.1 % clay fraction (<2 µm). According to the USCS soil classification, the expansive soil from the Nanyang site is CL.

2.3 Sample preparation

The dried and pressed sample first passed through a 2-mm sieve. Then the sample was mixed with distilled water. Seven groups of samples were prepared with water contents of 10 %, 12 %, 14 %, 16 %, 18 %, 20 %, and 22 %. The soil samples were stored in an airtight container for 96 hours to distribute the water evenly. The required quantity of samples was then put into a mold.

<table>
<thead>
<tr>
<th>Specific gravity $G_s$</th>
<th>Liquid limit $w_L$ (%)</th>
<th>Plastic limit $w_P$ (%)</th>
<th>Plasticity index $I_p$ (%)</th>
<th>Maximum dry density $\delta_{d,\text{max}}$ (Mg/m³)</th>
<th>Optimum water content $w_{opt}$ (%)</th>
<th>Free swelling ratio (%)</th>
<th>Unified Soil Classification System</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.73</td>
<td>52.7</td>
<td>23.7</td>
<td>29</td>
<td>1.68</td>
<td>18.9</td>
<td>49</td>
<td>CL</td>
</tr>
</tbody>
</table>

![Schematic diagram of testing apparatus.](image)
and compacted to different initial dry densities of 1.35, 1.50, or 1.65 Mg/m³. The specimen-preparation method is different from that of specimens undergoing drying from saturated specimens to specimens with different water contents [48]. It is known that in the drying process, the dry density of expansive soil will increase, and resulting in an increase in strength.

2.4 Test procedure

The diametric splitting tests were performed at a constant speed. The speed is 0.14 mm/min in the vertical direction. The tensile load and displacement were monitored during the testing. For each test group, two parallel specimens were prepared to check the procedural reproducibility.

2.5 Image processing

Surface deformation was monitored during the tests using the PIV system with images taken at 7-s intervals. After the tests, the images were changed to grayscale images and the study area with 60 × 60 mm² around the specimen (as shown in Figure 1) was selected and imported into the programs PIVview2C and Tecplot10 for the image analyses. Deformation information at different stages was obtained by comparing the images with the reference images taken prior to the tests. The length and orientation of the vectors representing the deformation are shown in the displacement vector field.

2.6 Soil-water characteristic curve test

The specimen-preparation method used in the soil-water characteristic curve test is the same as that used in the diametric splitting test. The suction was measured at different compaction water contents (6–22 %) of specimens with dry densities of 1.35, 1.50, and 1.65 Mg/m³ using the filter-paper method. Circular quantitative filter paper Whatman No. 42 was used for the filter paper method and the expression for determining the matrix suction from Leong et al. [15] is formulated as follows:

\[
\log s = 2.909 - 0.0229w_f \quad (w_f \geq 47) \quad (1)
\]

\[
\log s = 4.945 - 0.0673w_f \quad (w_f > 47) \quad (2)
\]

In the above formula, \( s \) is the matrix suction, and \( w_f \) is the water content of the filter paper.

Before the tests, the filter paper was kept in an oven at 105°C for more than 16 h to ensure dryness and then put in a dryer for cooling and storage. The soil specimen and filter paper contacted together and were put into a sealed box, which was held at constant temperature (20±2°C) and humidity for two weeks. After that the papers were quickly, carefully, and individually removed using forceps. The weight of the filter paper was measured with a balance having 0.0001-g precision and the water content of the filter paper was measured. The weight of the soil specimen was also measured. The matrix suction was calculated according to Eq. (1) or (2) and the soil-water characteristic curve (SWCC) was determined. More details about the suction measurement procedures can be found in Leong et al. [15].

3 RESULTS AND DISCUSSION

3.1 Soil-water characteristic curve of expansive soil

The results of the soil-water characteristic curves (SWCCs) tests for the expansive soil with different initial dry densities are shown in Fig. 3. The water content (\( w \)) and degree of saturation (\( S_r \)) both decrease with increasing suction. The relationships \( w-s \) and \( S_r-s \) are shown in Fig. 3a and Fig. 3b, respectively. The SWCCs move left and down with increasing initial dry density when the suction is less than 5000 kPa, as shown in Fig. 3a. The influence of the initial dry density on the soil-water characteristic curve is very obvious, especially for low suction, i.e., the water content decreases with increasing dry density under the same suction. When the suction is greater than 5000 kPa, the dry density's influence on the SWCCs is not apparent. A similar test result for SWCCs was found by Romeroe and Vanat [27] and Gao et al.

![Figure 3. Soil-water characteristic curves of expansive soil.](image-url)
In terms of the saturation degree, the SWCC curves move right and upwards with increasing dry density, as shown in Fig. 3b. The influence of the initial dry density on the soil-water characteristic curve is very obvious in the full suction range, the degree of saturation decreases with decreasing initial dry density under the same suction conditions, which is similar to that reported by Sun et al. [28], [29] and Sun and Sun [30].

3.2 Influence of initial dry density on the stress and strain behavior

The Influence of the initial dry density on the relationship between the load and the displacement of specimens with different water contents is shown in Fig. 4. For the plastic soil, the relationship between the load and the displacement of

![Graphs showing the influence of initial dry density on the relationship between load and displacement for different water contents.](image-url)
and the displacement in the splitting tests appears as a double-peak phenomenon. However, the soil underwent substantial plastic deformation in the second peak stage, which indicates that the stage poses little significance for studying the tensile strength. We therefore focus mainly on the curves in the first peak stage.

The results in Fig. 4 also show that the influence of the initial dry density on the tensile strength is very obvious. Under the same water-content conditions, the peak load increases with increasing initial dry density. As shown in Fig. 4a, when the water content is 10 %, the average peak load increases by 322.1 % and 1065.7 % as the dry density increases from 1.35 to 1.50 and from 1.35 to 1.65 Mg/m³, respectively. A similar test result was found by Blazejczak et al. [3]. This is because the specimen with a higher initial dry density has more contacts between the soil particles, and the number of water bridges increased, which leads to a higher peak load. The test results are more obvious, especially for expansive soil with a low water content.

The average increases of the peak load as the initial dry density increases from 1.35 to 1.50 Mg/m³ and to 1.65 Mg/m³ are shown in Figure 5. The average increase of the peak load decreases with increasing water content. Above, a similar test result was obtained by Li et al. [16].

3.3 Influence of water content on tensile stress-strain behavior

The influence of the initial water content on the relationship between the load and the displacement at different initial dry densities is shown in Fig. 6, which shows that the peak load first increases and then decreases with an increasing water content. The displacement where the relationship curve between the load and stress reaches the first peak value essentially increases with the water content. When the initial dry density is 1.35 Mg/m³, the peak value increases in the water content range from about 10 % to 18 %, and decreases from 18 % to 22 %. However, when the initial dry density is 1.50 and 1.65 Mg/m³, the peak value increases in the water content range from 10 % to 14 % and decreases from 14 % to 22 %. In addition, part of the slope of the curve that reaches the first peak value is larger with lower water content, which indicates that the brittleness is more apparent for compacted expansive soil with a low water content.

**Figure 5.** Average increase of peak load at different water contents with increasing initial dry density from 1.35 to 1.50 Mg/m³ and from 1.50 to 1.65 Mg/m³.

**Figure 6.** Effect of water content on the relationship between load and displacement.
There is a close functional relationship between the tensile strength and the suction for unsaturated soils [20], [32], [40]. As soils are subjected to drying conditions and the suction increases during the drying [50], which increases the tensile strength [39]. The peak-load characteristic curves (PLCCs) are shown in Fig. 7, which are according to relationship between the load and displacement in Fig. 6. And the soil-water characteristic curves (i.e., SWCCs) are also presented in Fig. 7.

Fig. 7 indicates that the PLCCs are unimodal curves and the PLCCs is influenced by the water content. Tang et al. [35] obtained similar results. The critical water content, \( w_c \) (~17.9 %, ~14.1 %, ~13 %), corresponding to the maximum peak load (65.5, 114.2, and 263.9 N) for different initial dry densities of 1.35, 1.50 and 1.65 Mg/m³ are determined from Figure 7. When \( w \) is less than \( w_c \), the peak load increases with an increase in the water content. However, when the water content is higher \( w_c \), the peak load decrease with an increase in the water content. The reason is as follows.

The change of microstructure with water content should be considered [40]. Most of the water is stored inside the aggregate pores at low water contents and it is very difficult to form liquid bridges [10]. The soil's tensile strength depends mainly on the liquid bridges among the particles. When \( w \) is less than \( w_c \), the liquid bridges form gradually with an increasing water content, and thus the peak load (tensile strength) increases with an increasing water content.

When the water content increases up to \( w_c \), the liquid bridges appear at most contact points of particles. The liquid bridges among the particles will disappear gradually with a further increasing water content, resulting in a decrease in the tensile strength.

### 3.4 Effects of initial dry density and water content on the displacement vector field

Figs. 6 and 8 show that the water content has a very obvious effect on the tensile strength. The images taken during the tests were analyzed, with the initial image taken immediately prior to the load application. The PIV and DIC techniques allow characterization of the evolution of the deformation patterns. Typical results are presented in Fig. 9 and are related to specimens at low

![Figure 7. PLCCs and SWCCs at different initial dry densities.](image)

![Figure 8. Typical relationship between load and displacement (\( \rho_d = 1.50 \text{ Mg/m}^3 \)).](image)
water contents (i.e., $w = 10\%$), around $w_c$ (i.e., $w = 14\%$), and a high water content (i.e., $w = 22\%$) and with an initial dry density of 1.50 Mg/m$^3$.

As shown in Fig. 8, the load-displacement curve of compacted, expansive soil with different water contents can be separated into four stages: a stress contact adjustment stage (I), for section OA, which is caused by the stress concentration of the upper and lower indenters on the contact parts of the specimens; stress approximately linearly increasing stage (II), for section AB, in which the load increases practically linearly with increasing displacement until reaching the peak (i.e., tensile strength); tensile failure stage (III), for section BC,
where the specimen begins to crack and the curve drops steeply after reaching the target value; and the residual stage (IV) for section CD, where the specimen shows clear splitting cracks, the curve decreases rapidly to zero and the specimen subsequently shows a certain residual strength. With increasing stress, the crack continues to expand until it is completely destroyed.

The fracture propagation of specimens with different water contents and their displacement vector fields are shown in Fig. 9. After the applied load experiences the AB segment, which is an approximately straight line, no obvious crack appears when the peak stress point B is reached. After the load drops to point C, a splitting crack appears on the splitting surface and the load drops sharply to point D. The fracture diagram and its displacement vector field of points B, C, and D are shown in Fig. 9a–9c, respectively. According to the displacement vector field in Fig. 9, the specimen at point B only underwent compression deformation without the formation of obvious cracks, owing to the plasticity of the soil mass. After the peak, cracks appear at point C and the displacement vector field is distributed symmetrically on both sides of the splitting surface. At point D, the load drops to the trough and the cracks connect. The failure part of the specimen is due to excessive displacement and the displacement vector field obtained by the PIV technique is a blank area. Moreover, the above phenomenon first increases and then decreases with increasing water content, which is most apparent at the optimal water content (i.e., \( w = 14 \% \)), and the time required to complete the II–IV stages shows a similar trend with the increasing water content.

Figs. 5 and 10 show that the initial dry density has a very obvious effect on the tensile strength. The images taken during the tests were analyzed, with the initial image taken immediately prior to the application of the tensile load. The evolution of the deformation patterns is characterized using the PIV and DIC techniques. The typical results are presented in Fig. 11, and are related to specimens with different initial dry densities (1.35, 1.50, and 1.65).

![Figure 9](image1.png)

**Figure 9.** Failure process and displacement vector field for specimens with different water contents.

![Figure 10](image2.png)

**Figure 10.** Typical relationship between load and displacement (\( w = 14 \% \)).
1.65 Mg/m³), and with a water content of 14 %. Under the same water content, the angle between the major direction of the displacement vector and the major crack decreases with increasing dry density, especially at point C, as two arrows show in middle figures of Fig. 11(a), (b) and (c). The above phenomenon might be caused by the specimens becoming increasingly hard as the dry density increases and the lateral displacement of the specimens decreases. Similar test results are observed for other specimens with different water contents ($w = 10\%–22\%$).
4 CONCLUSIONS

A newly designed diametric splitting testing apparatus and particle-image-velocimetry (PIV) system were employed to study the tensile stress-strain in a full-failure process of expansive soil systematically. The main conclusions are as follows.

1. The diametric splitting test process can be divided into four stages on the basis of the plotted peak load-displacement curves: stress contact adjustment stage (I); stress approximately linear increasing stage (II); tensile failure stage (III); and residual stage (IV).

2. The water content and the initial dry density have obvious effects on the tensile behavior of the compacted expansive soil. The tensile strength increases first and then decreases with increasing water content, and there is a critical water content. The critical water contents are about of 17.9 %, 14.1 %, and 13 % for expansive soil specimens with initial dry densities of 1.35, 1.50, and 1.65 Mg/m³, respectively. The peak load increases with increasing dry density, which is more obvious at a low water content.

3. The PIV techniques can be applied to analyze the deformation during testing, which provides the displacement vector field at various stages. Under the same water content, the angle between the major direction of the displacement vector field and the major crack decreases with increasing dry density, especially when the fissure appears. The tensile fissures and the directions of the propagation of major displacement vector field can be determined, which reflects the tensile stress distribution characteristics in the soil.

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