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*Research Article*

# Triaxial Wetting Test on Rockfill Materials under Stress Combination Conditions of Spherical Stress *p* and Deviatoric Stress *q*

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A GCTS medium-sized triaxial apparatus is used to conduct a single-line method wetting test on three kinds of rockfill materials of different mother rocks such as mixture of sandstone and slate, and dolomite and granite, and the test stress conditions is the combination of spherical stress $p$ and deviatoric stress $q$. The test results show that (1) for wetting shear strain, the effects of spherical stress $p$ and deviatoric stress $q$ are equivalent, and wetting shear strain and deviatoric stress $q$ show the power function relationship preferably. (2) For wetting volumetric strain, the effect of deviatoric stress $q$ can be neglected because it is extremely insignificant, and spherical stress $p$ is the main influencing factor and shows the power function relationship preferably. (3) The wetting strains decrease significantly with the increase in initial water content and sample density generally, but the excessively high dry density will increase the wetting deformation. Also, the wetting strains will decrease with the increase in the saturated uniaxial compressive strength and average softening coefficient of the mother rock. Based on the test results, a wetting strain model is proposed for rockfill materials. The verification results indicate that the model satisfactorily reflects the development law of wetting deformation.

## 1. Introduction

During the impounding process of core-wall rockfill dam, the rockfill materials of upstream dam shell usually experience the transition from "dry" to "wet." Therefore, materials will be softened to a certain extent. The contact parts of the particles may be fragmented, thus the internal structure of rockfill body may be adjusted. It will eventually produce significant wetting deformation which may cause local collapsibility and threatens the dam safety.

In 1972, based on some monitoring data of dam bodies, Nobari and Duncan [1] investigated the development laws of stress and strain of earth-rockfill dams in impoundment and paid close attention to the effect of water on material properties. Since then, numerous wetting studies have been conducted on various kinds of rockfill materials [2–6], and multiple wetting models for rockfill materials have been developed [7–15]. The wetting test usually is adopted with two methods of "double-line" and "single-line." The previous studies show that the single-line wetting test coincides with the process of impounding and wetting preferably [12, 16]. In single-line wetting tests, the stress conditions are usually adopted: the combination of confining pressure $\sigma_3$ and stress level $S_l$, and the wetting model usually expressed as a function of confining pressure $\sigma_3$ and stress level $S_l$. Actually, the impoundment process of the dam is usually accompanied by the simultaneous changes with confining pressure $\sigma_3$ and stress level $S_l$. As Shen analysed [17] (Figure 1), during the rise of water level, the spherical stress of upstream dam shell rockfill materials clearly decreases, the deviatoric stress slightly changes, and the stress level increases. Generally, volumetric strain $\varepsilon_v$ and shear strain $\varepsilon_s$

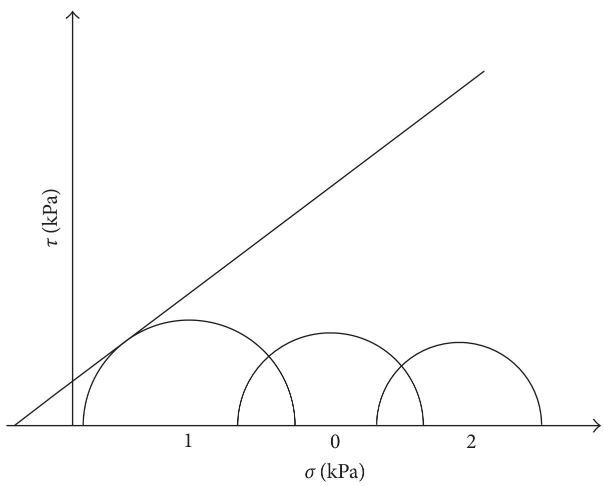


Figure 1: Stress circle change caused by impounding [1].

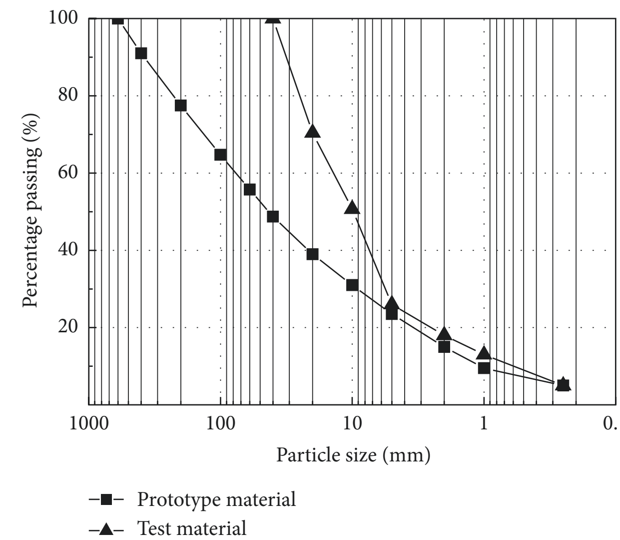


Figure 2: Grain-size distribution curve of test material.

have closer relationships with spherical stress $p$ and deviatoric stress $q$, respectively, and as the basic variables, spherical stress $p$ and deviatoric stress $q$ are usually adopted in some models including Cambridge elastic–plastic model and its modified model [18, 19]. On that account, it is more favourable to adopt spherical stress $p$ and deviatoric stress $q$ as the basic variables of wetting tests and models.

In this study, a single-line wetting test conducted by a medium-sized triaxial apparatus is introduced using three kinds of rockfill materials whose mother rocks are the mixed of sandstone and slate and dolomite and granite . Spherical stress $p$ and deviatoric stress $q$ are used as the stress combination. The effects of spherical stress $p$ and deviatoric stress $q$ on the wetting deformation of rockfill materials are investigated.

## 2. Test Scheme

*2.1. Test Materials and Equipment.* For the mixed rockfill materials, the mother rocks consist of sandstone (~60%) and slate (~40%). Sandstone has a saturated uniaxial compressive strength of >60 MPa and an average softening coefficient of 0.77, and slate has a saturated uniaxial compressive strength of 30–40 MPa and an average softening coefficient of 0.67. Dolomite has a saturated uniaxial compressive strength of 45–85 MPa and an average softening coefficient of 0.67–0.87, and granite has a saturated uniaxial compressive strength of 62–94 MPa and an average softening coefficient of 0.80–0.97.

The rockfill materials of natural gradation have a maximum particle size of 600 mm. According to *the test methods of soils* [20], the method of *mixing gradation scale* is used to obtain the test gradation in which the maximum particle size is 40 mm. The gradation curves of rockfill materials are shown in Figure 2, and the gradation data are shown in Table 1. The triaxial test apparatus manufactured by GCTS (USA) is used. Both the confining and axial pressures are provided using a servo pressure controller with a pressure control precision of 0.5 kPa. A confining pressure–volume controller is used to measure the change of water quantity in the confining pressure cell with the measurement accuracy of 0.01 ml. The test sample diameter is 200 mm and the height is 400 mm.

*2.2. Test Procedure.* Firstly, the confining pressure $\sigma_3$ and axial stress $\sigma_1$ based on the designed stress conditions are calculated. Secondly, the confining pressure is applied and the designed confining pressure stable was kept until the specimen deformation is stable under the isotropic stress. The sample is in contact with the atmosphere during this process. Thirdly, the axial strain rate (0.5%/min) is adopted until the designed axial stress is reached and also the deformation stability of the specimen under the stress state needs to be achieved. Finally, the sample will gradually be wetted and saturated from bottom to top (the water head of wetting test is about 60 cm). It indicates that the wetting deformation has been completed when no continuous bubbles are observed in the drain pipe; meanwhile, the sample has been stabilized as per the standard of deformation stability. Both under the isotropic stress and wetting process, the stabilization standard of sample deformation is 0.001%/min as the average axial strain rate within 10 min.

The parameters used in this study are provided in the following formulas: spherical stress $p = (\sigma_1 + 2\sigma_3)/3$ and deviatoric stress $q = \sigma_1 - \sigma_3$, where $\sigma_1$ and $\sigma_3$ represent the axial stress and confining pressure, respectively. Sample volumetric strain $\varepsilon_v = (v_{cell} + v_{piston})/v_0$, where $v_{cell}$ is the volume change of water in the confining pressure cell, $v_{piston}$ is the volume of the loading piston entering the pressure cell, and $v_0$ is the sample volume after the isotropic stress and deformation stabilization. In this study, volume expansion is taken as negative, and volume compression is taken as

Table 1: Grain-size distribution data of test material.

| Materials | Percentage passing (%) | | | | | | | | | | | | $d_{60}$ | $d_{30}$ | $d_{10}$ | $C_u$ | $C_c$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 600 | 400 | 200 | 100 | 60 | 40 | 20 | 10 | 5 | 2 | 1 | 0.25 | | | | | |
| Prototype | 100 | 91 | 77.5 | 64.8 | 55.8 | 48.8 | 39.0 | 31.0 | 23.5 | 15.0 | 9.5 | 5 | 76 | 9.1 | 1.1 | 69 | 0.9 |
| Test | — | — | — | — | — | 100.0 | 70.4 | 50.7 | 26.0 | 18.0 | 13.0 | 5 | 14 | 5.8 | 0.7 | 20 | 3.4 |

positive. Shear strain $\varepsilon_s = \varepsilon_a - \varepsilon_v \times 1/3$, where $\varepsilon_a$ is the axial strain.

## 3. Wetting Test Results

*3.1. Stress Conditions of Equal p and Unequal q.* In accordance with the combination of spherical stress $p$ and deviatoric stress $q$ designed in the test, the stress conditions included five spherical stress $p$ conditions, each corresponding to 3–5 deviatoric stress $q$ conditions. The stress conditions of the test and corresponding wetting deformation results are shown in Table 2. The dry density of the test sample is 2.18 g/cm$^3$, the test materials are air-dried, and the water content of test rockfill materials whose maximum size is equal to 5 mm is 0.4%.

Based on the wetting test results, the curves of wetting volumetric strain and wetting shear strain with deviatoric stress under different spherical stress conditions are plotted, as shown in Figures 3 and 4. As indicated by the results, the deviatoric stress exerts varying effect on both the wetting volumetric strain and shear strain. With the increase in deviatoric stress, the wetting shear strain shows significant increasing trend. The wetting volumetric strain also shows an increasing trend with the increase in deviatoric stress, but the magnitude of increase is not obvious. Corresponding to the five spherical stress conditions, the wetting shear strain increases by about 2.33, 1.0, 1.67, 1.4, and 3.44 times respectively, when deviatoric stress increased from its minimum value to the maximum value. However, the wetting volumetric strain only increases by about 0.15, 0.09, 0.08, 0.07, and 0.08 times, respectively, indicating that the effect of deviatoric stress on wetting volumetric strain is extremely insignificant.

Table 2: Test stress conditions and test results (stress conditions of equal $p$ and unequal $q$).

| Test stress | | Test results | | |
|---|---|---|---|---|
| $p$ (kPa) | $q$ (kPa) | $\varepsilon_a$ (%) | $\varepsilon_v$ (%) | $\varepsilon_s$ (%) |
| 1000 | 300 | 0.69 | 1.17 | 0.30 |
| | 500 | 0.83 | 1.22 | 0.42 |
| | 670 | 0.95 | 1.28 | 0.52 |
| | 1000 | 1.24 | 1.35 | 0.79 |
| 1500 | 900 | 1.42 | 1.85 | 0.80 |
| | 1500 | 1.94 | 1.93 | 1.30 |
| | 1800 | 2.20 | 2.01 | 1.53 |
| 2000 | 900 | 1.42 | 2.16 | 0.70 |
| | 1500 | 1.85 | 2.18 | 1.12 |
| | 2000 | 2.29 | 2.26 | 1.53 |
| | 2400 | 2.65 | 2.34 | 1.87 |
| 2500 | 1250 | 1.63 | 2.31 | 0.86 |
| | 1670 | 1.93 | 2.33 | 1.15 |
| | 3000 | 3.08 | 2.47 | 2.26 |
| 3000 | 900 | 1.40 | 2.63 | 0.52 |
| | 1500 | 1.85 | 2.68 | 0.96 |
| | 2000 | 2.22 | 2.72 | 1.31 |
| | 3000 | 3.05 | 2.80 | 2.12 |
| | 4000 | 3.95 | 2.85 | 3.00 |

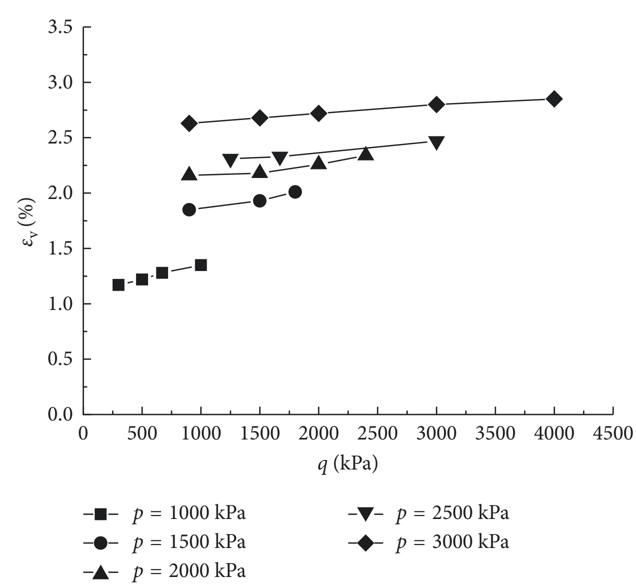


Figure 3: $q$ versus $\varepsilon_v$ curve (stress conditions of equal $p$ and unequal $q$).

*3.2. Stress Conditions of Equal q and Unequal p.* Based on the above test, the test under some stress conditions is supplemented. As per the combination of spherical stress $p$ and deviatoric stress $q$, the test introduced three deviatoric stress $q$ conditions, each corresponding to 3-4 spherical stress $p$ conditions. The stress conditions and wetting deformation results are shown in Table 3. Based on the wetting test results, the curves of wetting volumetric strain and wetting shear strain with spherical stress under deviatoric stress conditions are plotted, as shown in Figures 5 and 6.

The spherical stress shows the relatively obvious effect on both wetting volumetric strain and shear strain. Wetting shear strain decreased with the increase in spherical stress, and the wetting volumetric strain increased with the increase in spherical stress. Corresponding to three deviatoric stress conditions, when spherical stress increased from its minimum value to the maximum value, (i.e., increased by about 2, 2, and 0.36 times, resp.), the wetting shear strain decreases by about 0.35, 0.26, and 0.14 times, and the wetting volumetric strain increased by about 0.42, 0.39, and 0.17 times, respectively. The results indicate that spherical stress exerts the same degree of effect on the wetting volumetric strain and shear strain.

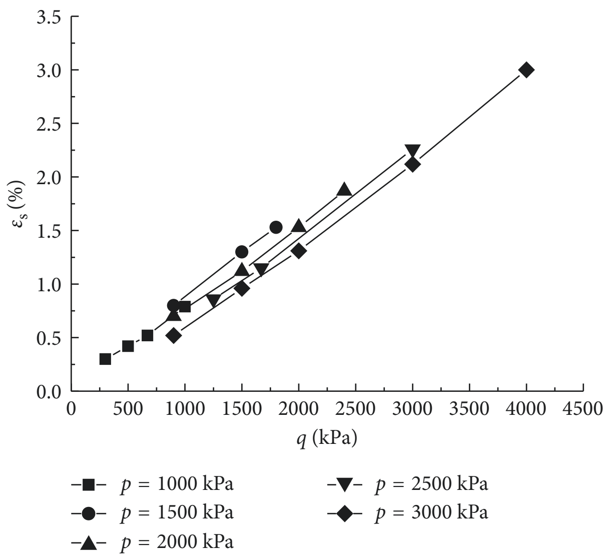


Figure 4: $q$ versus $\varepsilon_s$ curve (stress conditions of equal $p$ and unequal $q$).

Table 3: Test stress conditions and test results (stress conditions of equal $q$ and unequal $p$).

| Test stress | | Test results | | |
|---|---|---|---|---|
| $q$ (kPa) | $p$ (kPa) | $\varepsilon_a$ (%) | $\varepsilon_v$ (%) | $\varepsilon_s$ (%) |
| 900 | 1500 | 1.42 | 1.85 | 0.80 |
| | 2000 | 1.42 | 2.16 | 0.70 |
| | 3000 | 1.40 | 2.63 | 0.52 |
| 1500 | 1500 | 1.94 | 1.93 | 1.30 |
| | 2000 | 1.85 | 2.18 | 1.12 |
| | 3000 | 1.85 | 2.68 | 0.96 |
| 3000 | 2200 | 3.08 | 2.47 | 2.26 |
| | 2500 | 3.06 | 2.65 | 2.18 |
| | 2700 | 3.05 | 2.80 | 2.12 |
| | 3000 | 1.42 | 1.85 | 0.80 |

*3.3. Initial Water Content.* To research the effect of different initial water contents on wetting deformation, the water content of the test materials (maximum size <5 mm) is prepared according to particle weights, and the sample water contents are 5% and 10%. The sample dry density is 2.18 g/cm$^3$. In this test, the spherical stress p is set at 2,000 kPa, and the deviatoric stress q is set at 900 kPa, 1,500 kPa, and 2,400 kPa. The gradation and test procedure of the test materials are the same as described above. The stress conditions and wetting deformation results of the test are shown in Table 4.

Clearly, with the increase in the sample's initial water content, the wetting strains decrease significantly, indicating that the initial water content is an important factor influencing the wetting deformation of materials. Under the three deviatoric stress conditions (from low to high), when the initial water content increases from 0.4% to 5%, the wetting volumetric strain decreases by about 0.51%, 0.48%, and 0.59%, and the wetting volumetric strain decreases by about 0.80%, 0.80%, and 0.77%. Under the three deviatoric stress conditions (from low to high), when the initial water content increased from 5 to 10%, the wetting shear strain decreases by about 0.12%, 0.24%, and 0.33%, and the wetting volumetric strain decreases by about 0.41%, 0.42%, and 0.50%, respectively.

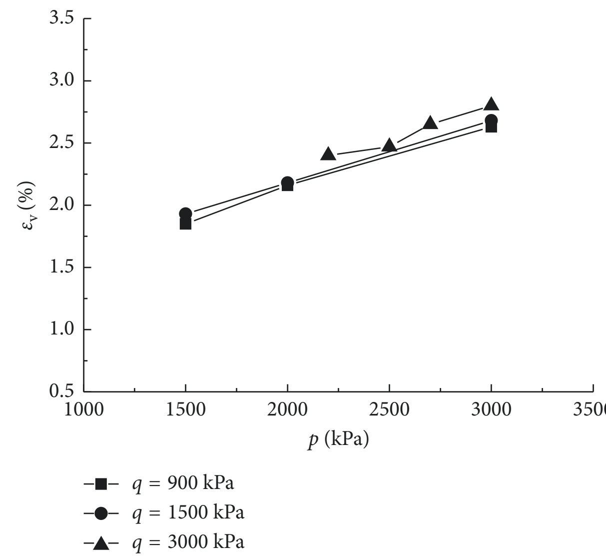


Figure 5: $p$ versus $\varepsilon_v$ curve (stress conditions of equal $q$ and unequal $p$).

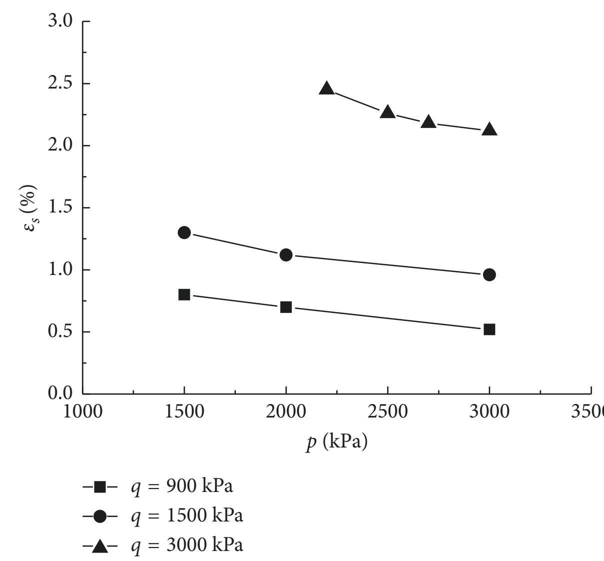


Figure 6: $p$ versus $\varepsilon_s$ curve (stress conditions of equal $q$ and unequal $p$).

The results indicate that the wetting deformation will decrease significantly as the water content of fine particles increases. Adopting suitable watering on materials during dam construction will not only improves the compaction of dam body, but also reduces the wetting deformation.

*3.4. Sample Density.* To investigate the effect of different sample densities on wetting deformation, two sample dry densities ($\rho_d$) are designed, that is, 2.12 g/cm$^3$ and 2.05 g/cm$^3$. In the test, the spherical stress $p$ is 2,000 kPa, and the deviatoric stress $q$ is set at 900 kPa, 1,500 kPa, and 2,400 kPa. The test procedure is the same as described above,

Table 4: Test stress conditions and test results (different initial water contents).

| $\omega$ (%) | Test stress | | Test results | | |
|---|---|---|---|---|---|
| | $p$ (kPa) | $q$ (kPa) | $\varepsilon_a$ (%) | $\varepsilon_v$ (%) | $\varepsilon_s$ (%) |
| 0.4 | 2000 | 900 | 1.42 | 2.16 | 0.70 |
| | | 1500 | 1.85 | 2.18 | 1.12 |
| | | 2400 | 2.65 | 2.34 | 1.87 |
| 5 | 2000 | 900 | 1.13 | 1.65 | 0.58 |
| | | 1500 | 1.45 | 1.70 | 0.88 |
| | | 2400 | 2.12 | 1.75 | 1.54 |
| 10 | 2000 | 900 | 0.45 | 0.85 | 0.17 |
| | | 1500 | 0.76 | 0.90 | 0.46 |
| | | 2400 | 1.36 | 0.98 | 1.03 |

Table 5: Test stress conditions and test results (different dry densities).

| $\rho_d$ (g/cm$^3$) | Test stress | | Test results | | |
|---|---|---|---|---|---|
| | $p$ (kPa) | $q$ (kPa) | $\varepsilon_a$ (%) | $\varepsilon_v$ (%) | $\varepsilon_s$ (%) |
| 2.18 | 2000 | 900 | 1.42 | 2.16 | 0.70 |
| | | 1500 | 1.85 | 2.18 | 1.12 |
| | | 2400 | 2.65 | 2.34 | 1.87 |
| 2.12 | 2000 | 900 | 1.27 | 1.78 | 0.68 |
| | | 1500 | 1.71 | 1.86 | 1.09 |
| | | 2400 | 2.36 | 1.92 | 1.72 |
| 2.05 | 2000 | 900 | 1.82 | 2.36 | 1.03 |
| | | 1500 | 2.20 | 2.45 | 1.38 |
| | | 2400 | 3.15 | 2.55 | 2.30 |

and the test materials are air-dried. The stress conditions and wetting deformation results are shown in Table 5.

Clearly, with the increase in sample density, the wetting deformation decreases firstly and then slightly increased, but the wetting deformation shows decreasing trend on the whole when the sample density increases from 2.05 g/cm$^3$ to 2.18 g/cm$^3$, in which when $\rho_d$ increases from 2.05 g/cm$^3$ to 2.12 g/cm$^3$, the wetting volumetric strain decreases by about 24%, and the wetting shear strain decreases by 20–35%. When $\rho_d$ increases from 2.12 g/cm$^3$ to 2.18 g/cm$^3$, the wetting volumetric strain increases by 17–22%, and the wetting shear strain increases by 3–10%.

The results indicate that, with the increase in sample density, the porosity of rockfill materials decreased, causing closer contacts among rockfill particles and reducing the wetting deformation. But when the sample density is further increased, more fragmentation of rockfill materials during the sample preparation occurred due to excessively high density resulting in the content of fine particles in the test materials, and the wetting deformation increased consequently. During the filling and compacting process of rockfill materials, it is necessary to adopt appropriate compaction parameters and compaction density so as to reduce the wetting deformation. Especially it should avoid using excessively high compaction density which will make the wetting deformation increased.

*3.5. Mother Rock.* To study the effect of different the mother rock on wetting deformation, the other two kinds of materials with different mother rocks are adopted, such as dolomite and granite. For all the three materials, the gradation of rockfill materials is the same as shown in Figure 2 and also adopted with the same relative density. The sample density of dolomite and granite materials are 2.22 g/cm$^3$ and 2.05 g/cm$^3$, respectively, and the test materials are also air-dried.

In the test, the spherical stress p is 2,000 kPa, and the deviatoric stress q is set at 900 kPa, 1,500 kPa, and 2,400 kPa. The stress conditions and wetting deformation results are shown in Table 6.

The test results show that the mother rock has significant effect on wetting deformation. For the three kinds of test materials, the saturated uniaxial compressive strength and average softening coefficient of the mother rock decrease generally from granite, and dolomite to mixed materials. And both the wetting volumetric strain and wetting shear strain increase significantly 3–5 times, respectively, than granite materials. For granite materials, the wetting volumetric strain is just about 0.4%, and the wetting shear strain is just 0.1–0.4%; it shows that there is just slight wetting deformation for the rock with high strength due to less particle breakage during wetting process.

## 4. Single-Line Wetting Model

*4.1. Wetting Shear Strain Model.* As indicated by the deformation trend of wetting shear strain in Section 3, the wetting shear strain and deviatoric stress $p$ show relatively good power function relationship; the test results and power function fitting curves are plotted, as shown in Figure 7.

To be specific, the wetting test results are shown by icons of different shapes, and the power function relationships are expressed by curves. The relationship expression can be expressed as follows:

$$\varepsilon_s = a \cdot \left(\frac{q}{p_a}\right)^b, \tag{1}$$

where $a$ and $b$ are the fitting parameters related to the spherical stress $p$, $q$ is the wetting deviatoric stress, and $p_a$ is the standard atmospheric pressure, mainly introduced for the purpose of coordinating the magnitudes of deviatoric stress and wetting strain. Parameter $a$ mainly represents the development of the magnitude of wetting shear strain with normalized deviatoric stress $q$, and parameter $b$ mainly represents the development speed of the magnitude of wetting deformation with normalized deviatoric stress $q$.

The following values can be seen:

$p = 1000\,\text{kPa},\ \varepsilon_s = 0.108 \times (q/p_a)^{0.857},\ R^2 = 0.98$

$p = 1500\,\text{kPa},\ \varepsilon_s = 0.105 \times (q/p_a)^{0.929},\ R^2 = 0.99$

$p = 2000\,\text{kPa},\ \varepsilon_s = 0.071 \times (q/p_a)^{1.027},\ R^2 = 0.99$

$p = 2500\,\text{kPa},\ \varepsilon_s = 0.050 \times (q/p_a)^{1.120},\ R^2 = 0.99$

$p = 3000\,\text{kPa},\ \varepsilon_s = 0.039 \times (q/p_a)^{1.177},\ R^2 = 0.99$

Clearly, during deviatoric stress $q$ approached 0, the stress conditions of the sample are close to isotropic state, and the wetting shear strain approaches 0 as well. The trend

Table 6: Test stress conditions and test results (different mother rocks).

| Mother rock | $D_r$ | Test stress | | Test results | | |
|---|---|---|---|---|---|---|
| | | $p$ (kPa) | $q$ (kPa) | $\varepsilon_a$ (%) | $\varepsilon_v$ (%) | $\varepsilon_s$ (%) |
| Mixture of sandstone and slate | 0.80 | 2000 | 900 | 1.27 | 1.78 | 0.68 |
| | | | 1500 | 1.71 | 1.86 | 1.09 |
| | | | 2400 | 2.36 | 1.92 | 1.72 |
| Dolomite | 0.80 | 2000 | 900 | 0.87 | 1.19 | 0.47 |
| | | | 1500 | 1.15 | 1.25 | 0.73 |
| | | | 2400 | 1.63 | 1.32 | 1.19 |
| Granite | 0.80 | 2000 | 900 | 0.26 | 0.40 | 0.13 |
| | | | 1500 | 0.40 | 0.43 | 0.26 |
| | | | 2400 | 0.58 | 0.45 | 0.43 |

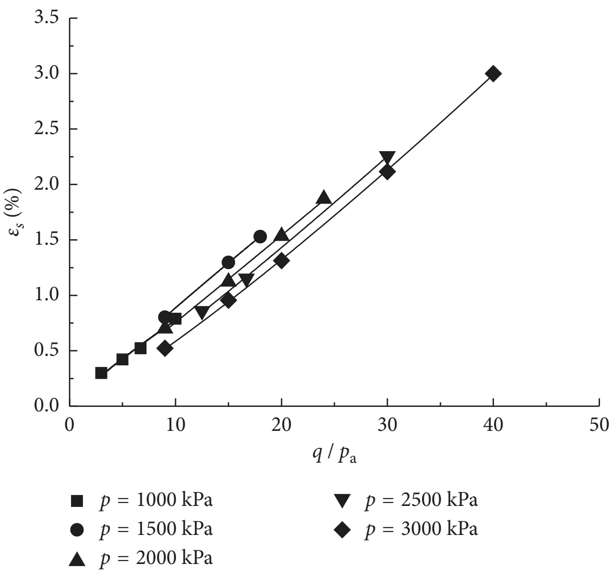


Figure 7: $q/p_a$ versus $\varepsilon_s$ curve (fitting of wetting shear strain).

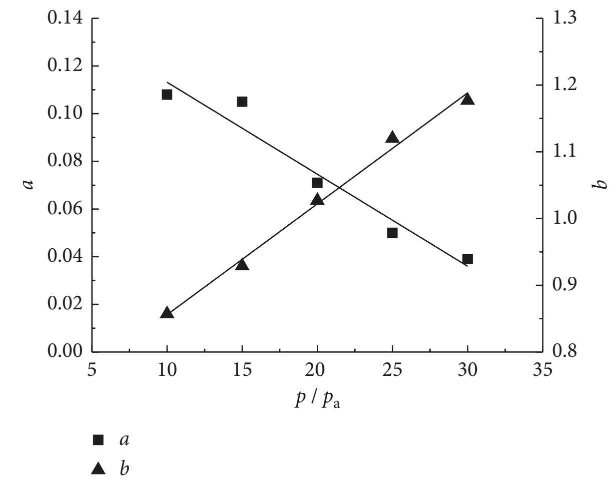


Figure 8: $a$, $b$ versus $p/p_a$ curve (fitting of parameters $a$ and $b$).

indicates that under isotropic conditions, the wetting shear strain of rockfill materials is not obvious. When the deviatoric stress $q$ increased, the corresponding confining pressure decreased, the axial stress increased, and the sample is at relatively high stress level. At this state, the wetting shear strain increases obviously and indicates that the effect of deviatoric stress on wetting shear strain is relatively significant.

Both the parameters $a$ and $b$ are related to spherical stress $p$ and the relationship curves of the two parameters with normalized spherical stress $p$ are plotted, as shown in Figure 8.

The wetting parameters $a$ and $b$ show relatively good linear relationship with normalized spherical stress. The curves indicate that

$$a = h + f \cdot \frac{p}{p_a}, \qquad b = k + g \cdot \frac{p}{p_a}. \tag{2}$$

The calculation formula for wetting shear strain can be deduced from (1) and (2):

$$\varepsilon_s = \left(h + f \cdot \frac{p}{p_a}\right) \cdot \left(\frac{q}{p_a}\right)^{(k+g\cdot(p/p_a)).} \tag{3}$$

The following values can be seen:

$a = 0.1515 - 0.0039 \times (p/p_a)$, $R^2 = 0.95$

$b = 0.6893 + 0.0166 \times (p/p_a)$, $R^2 = 0.99$

The results indicate that the wetting shear strain is related to $h$, $f$, $k$, and $g$. The wetting shear strain parameters of the test materials are as follows: $h = 0.1515$, $f = 0.0039$, $k = 0.6893$, and $g = 0.0166$. After substituting the wetting parameters into the calculation (3), the wetting shear strain of model calculation can be obtained. Comparison with the wetting shear strain measured experimentally and the model calculated are shown in Figure 9. The model calculation and experimental results show consistent trends (the test and model data are shown in Table 7), and the shear strain model relatively satisfactorily reflect the wetting test results.

*4.2. Wetting Volumetric Strain Model.* As indicated by the above results, spherical stress $p$ is the main factor influencing the wetting volumetric strain, and deviatoric stress $q$ exerts an extremely insignificant effect on wetting volumetric strain. Therefore, the effect of deviatoric stress on wetting volumetric strain in the wetting volumetric strain model is

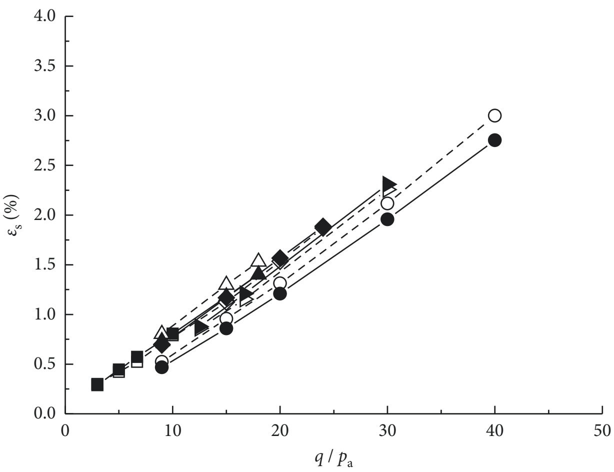


Figure 9: $\varepsilon_s$ versus $q$ curve (comparison of experimental and model results).

Table 7: Test stress conditions and results (compared with test results and model results for $\varepsilon_s$).

| Test stress | | $\varepsilon_s$ | | |
|---|---|---|---|---|
| $p$ (kPa) | $q$ (kPa) | Test results (%) | Model results (%) | Deviation (%) |
| 1000 | 300 | 0.30 | 0.29 | −4.03 |
| | 500 | 0.42 | 0.45 | 5.56 |
| | 670 | 0.52 | 0.57 | 9.37 |
| | 1000 | 0.79 | 0.81 | 2.05 |
| 1500 | 900 | 0.80 | 0.73 | −9.02 |
| | 1500 | 1.30 | 1.18 | −8.97 |
| | 1800 | 1.53 | 1.40 | −8.46 |
| 2000 | 900 | 0.70 | 0.69 | −0.97 |
| | 1500 | 1.12 | 1.17 | 3.97 |
| | 2000 | 1.53 | 1.57 | 2.09 |
| | 2400 | 1.87 | 1.89 | 0.94 |
| 2500 | 1250 | 0.86 | 0.88 | 2.15 |
| | 1670 | 1.15 | 1.21 | 4.89 |
| | 3000 | 2.26 | 2.31 | 2.36 |
| 3000 | 900 | 0.52 | 0.47 | −10.46 |
| | 1500 | 0.96 | 0.86 | −10.17 |
| | 2000 | 1.31 | 1.21 | −7.90 |
| | 3000 | 2.12 | 1.96 | −7.54 |
| | 4000 | 3.00 | 2.75 | −8.22 |

neglected. The relationship curves between normalized spherical stress $p$ of different magnitudes and wetting volumetric strain $\varepsilon_v$ are plotted, as shown in Figure 10.

Clearly, under the same spherical stress $p$ conditions, with the increase in spherical stress $p$, the wetting volumetric strain $\varepsilon_v$ increases with a change law of power function as

$$\varepsilon_v = s * \left(\frac{p}{p_a}\right)^t, \tag{4}$$

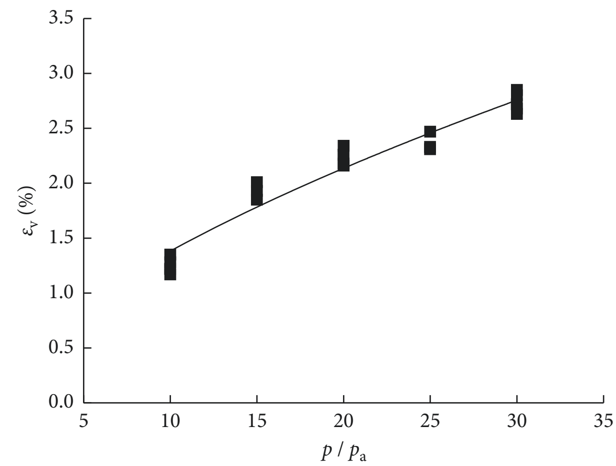


Figure 10: $p/p_a$ versus $\varepsilon_v$ curve (comparison of experimental and model results).

where $\varepsilon_v$ is the wetting volumetric strain, $s$ and $t$ are the test parameters of wetting volumetric strain, which are the same for the same material under the same test conditions and $p$ is the wetting spherical stress.

The following values can be seen:

$$\varepsilon_v = 0.3249 \times (p/p_a)^{0.6287},\ R^2 = 0.94$$

The wetting volumetric strain parameters of the test materials are as follows: $s = 0.3249$, and $t = 0.6287$. Clearly, the model calculation and experimental results are consistent, and the experimental and model data are shown in Table 8.

## 5. Model Verification

The relationship curves of wetting shear strain $\varepsilon_s$ and normalized wetting deviatoric stress $q$ under sample density, initial water content, and mother rock conditions are plotted, as shown in Figures 11–13, respectively. Under the three kinds of test conditions, the correspondence between wetting shear strain $\varepsilon_s$ and normalized wetting deviatoric stress $q$ can be relatively satisfactorily simulated with a power function in each case, and the fitting curves show very high correlation with the test results.

The following results can be seen:

$$\rho_d = 2.05\ \text{g/cm}^3,\ \varepsilon_s = 0.135 \times (q/p_a)^{0.888},\ R^2 = 0.95$$
$$\rho_d = 2.12\ \text{g/cm}^3,\ \varepsilon_s = 0.083 \times (q/p_a)^{0.953},\ R^2 = 0.99$$
$$\rho_d = 2.18\ \text{g/cm}^3,\ \varepsilon_s = 0.071 \times (q/p_a)^{1.027},\ R^2 = 0.99$$
$$\omega = 0.4\%,\ \varepsilon_s = 0.071 \times (q/p_a)^{1.027},\ R^2 = 0.99$$
$$\omega = 5\%,\ \varepsilon_s = 0.054 \times (q/p_a)^{1.051},\ R^2 = 0.98$$
$$\omega = 10\%,\ \varepsilon_s = 0.004 \times (q/p_a)^{1.782},\ R^2 = 0.99$$

Mixture of sandstone and slate: $\varepsilon_s = 0.083 \times (q/p_a)^{0.953}$, $R^2 = 0.99$

Dolomite: $\varepsilon_s = 0.055 \times (q/p_a)^{0.966}$, $R^2 = 0.99$

Granite: $\varepsilon_s = 0.011 \times (q/p_a)^{1.164}$, $R^2 = 0.99$

The curves between wetting volumetric strain $\varepsilon_v$ and normalized deviatoric stress $q$ under sample density, initial

Table 8: Test stress conditions and results (compared with test results and model results for $\varepsilon_v$).

| Test stress | | $\varepsilon_v$ | | |
|---|---|---|---|---|
| $p$ (kPa) | $q$ (kPa) | Test results (%) | Model results (%) | Deviation (%) |
| 1000 | 300 | 1.17 | 1.33 | −13.57 |
| | 500 | 1.22 | 1.33 | −8.89 |
| | 670 | 1.28 | 1.33 | −3.84 |
| | 1000 | 1.35 | 1.33 | 1.55 |
| 1500 | 900 | 1.85 | 1.75 | 5.40 |
| | 1500 | 1.93 | 1.75 | 9.33 |
| | 1800 | 2.01 | 1.75 | 12.93 |
| 2000 | 900 | 2.16 | 2.13 | 1.50 |
| | 1500 | 2.18 | 2.13 | 2.40 |
| | 2000 | 2.26 | 2.13 | 5.87 |
| | 2400 | 2.34 | 2.13 | 9.08 |
| 2500 | 1250 | 2.31 | 2.48 | −7.16 |
| | 1670 | 2.33 | 2.48 | −6.24 |
| | 3000 | 2.47 | 2.48 | −0.23 |
| 3000 | 900 | 2.63 | 2.80 | −6.54 |
| | 1500 | 2.68 | 2.80 | −4.55 |
| | 2000 | 2.72 | 2.80 | −3.01 |
| | 3000 | 2.80 | 2.80 | −0.07 |
| | 4000 | 2.85 | 2.80 | 1.68 |

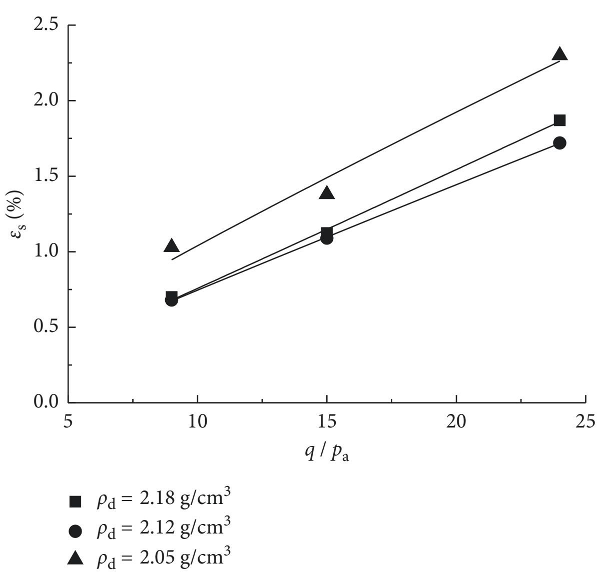


Figure 11: $q/p_a$ versus $\varepsilon_s$ curve (different sample dry density conditions).

water content, and mother rock conditions are plotted, as shown in Figures 14–16, respectively. Under the three kinds of test conditions, wetting volumetric strain $\varepsilon_v$ and normalized deviatoric stress $q$ uniformly shows linear function relationship, and the fitting curves shows very high correlation with the test results. However, the slope of the linear relationship curves indicates the insignificant effect of deviatoric stress $q$ on the wetting volumetric strain.

The following results can be seen:

$$\rho_d = 2.05\ \mathrm{g/cm^3},\ \varepsilon_v = 2.252 + 0.012 \times (q/p_a),\ R^2 = 0.99$$

$$\rho_d = 2.12\ \mathrm{g/cm^3},\ \varepsilon_v = 1.707 + 0.009 \times (q/p_a),\ R^2 = 0.92$$

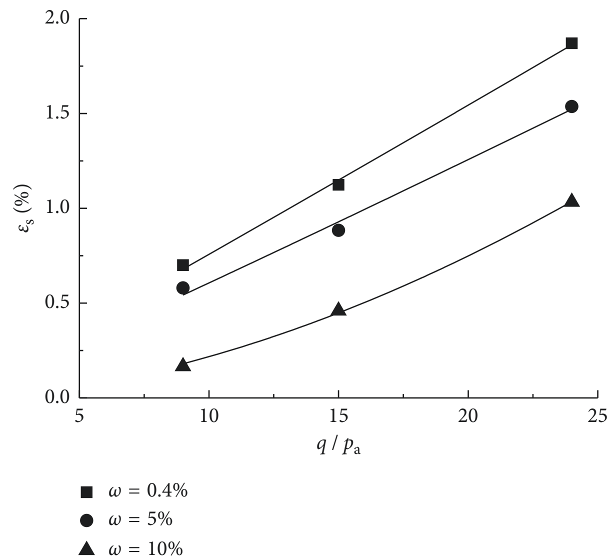


Figure 12: $q/p_a$ versus $\varepsilon_s$ curve (different initial water content conditions).

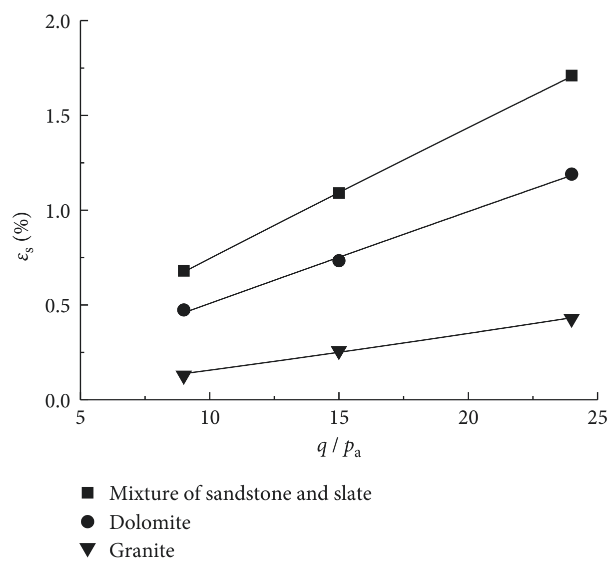


Figure 13: $q/p_a$ versus $\varepsilon_s$ curve (different mother rocks).

$$\rho_d = 2.18\ \mathrm{g/cm^3},\ \varepsilon_v = 2.027 + 0.012 \times (q/p_a),\ R^2 = 0.82$$

$$\omega = 0.4\%,\ \varepsilon_v = 2.027 + 0.012 \times (q/p_a),\ R^2 = 0.82$$

$$\omega = 5\%,\ \varepsilon_v = 1.595 + 0.007 \times (q/p_a),\ R^2 = 0.97$$

$$\omega = 10\%,\ \varepsilon_v = 0.771 + 0.009 \times (q/p_a),\ R^2 = 0.99$$

Mixture of sandstone and slate: $\varepsilon_v = 1.707 + 0.009 \times (q/p_a),\ R^2 = 0.92$

Dolomite: $\varepsilon_v = 1.116 + 0.009 \times (q/p_a),\ R^2 = 0.99$

Granite: $\varepsilon_v = 0.375 + 0.003 \times (q/p_a),\ R^2 = 0.90$

## 6. Conclusions

A single-line wetting test is conducted on three kinds of rockfill materials of different mother rocks such as mixed of

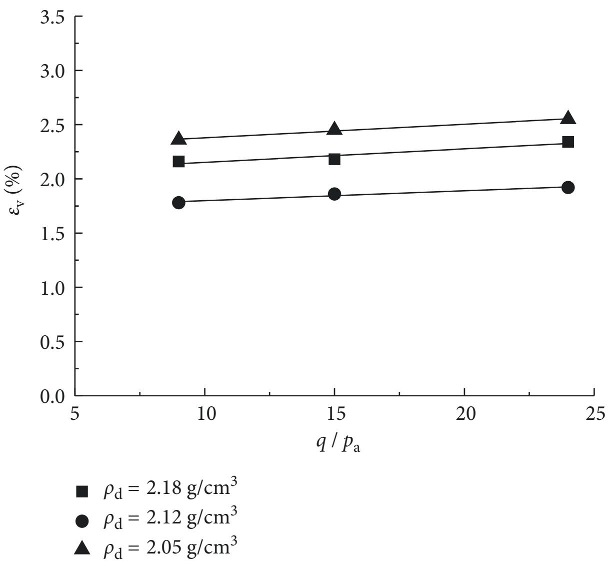


FIGURE 14: $q/p_a$ versus $\varepsilon_v$ curve (different sample dry density conditions).

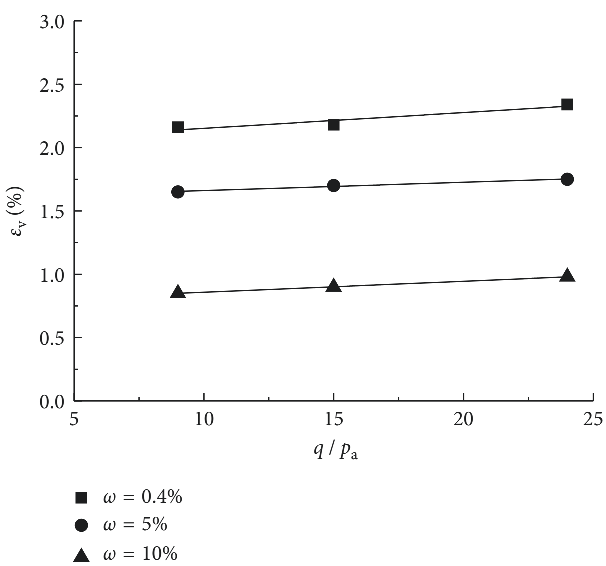


FIGURE 15: $q/p_a$ versus $\varepsilon_v$ curve (different initial water content conditions).

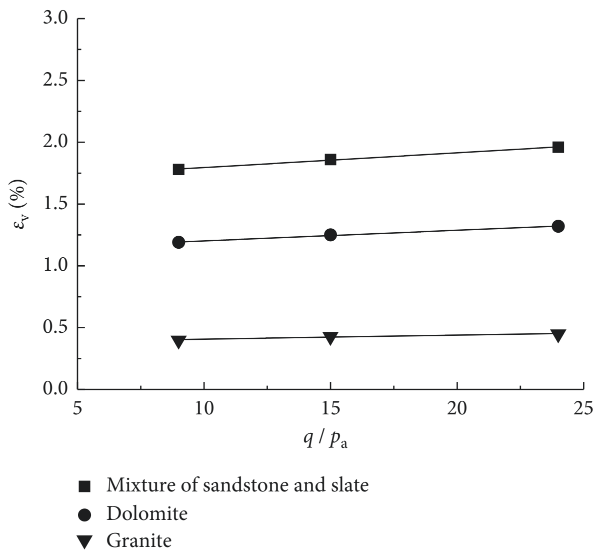


FIGURE 16: $q/p_a$ versus $\varepsilon_v$ curve (different mother rock).

sandstone and slate, and dolomite and granite under the stress combination conditions of spherical stress $p$ and deviatoric stress $q$, and the effects of initial water content, sample density, and mother rocks on the wetting deformation also are performed. The relationships between wetting strain characteristics and stress conditions are obtained. Based on the wetting test on rockfill materials under different stress conditions, a wetting strain model for rockfill materials and the related wetting parameters are proposed, and the model is verified with several test conditions. The verification results indicate that the model relatively satisfactorily reflects the development trend of wetting deformation. It should be noted that the process of the wetting deformation of rockfill materials is complex, and it is affected by numerous factors. In order to improve the accuracy of the wetting model, further studies are still needed.

## 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 there are no conflicts of interest regarding the publication of this paper.

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