INTRODUCTION

With the depletion of shallow underground resources and the increasing demand for energy, underground mining in China and other countries has gradually shifted to deeper levels. The continuous extension of mining depth poses a great threat to the safe and efficient production.1-6 Under high temperature, high humidity, high pressure, and high...
osmotic pressure, deep rock masses exhibit completely different mechanical properties and failure characteristics from shallow rock masses. The mechanical properties of deep rock masses have become the focus of research worldwide.7-14 Tensile failure or tensile shear failure of rocks is the main failure mode of surrounding rocks in underground engineering. Therefore, the tensile strength of rocks is a key indicator for evaluating the stability of roadways in underground engineering. In a high-humidity deep underground environment, expansion stress is generated inside an expansive soft rock under the influence of water infiltration. Under a coupled action of humidity and stress, the characteristics of the tensile failure of the rock mass are completely different from those under a single geostress. Therefore, the tensile failure mechanism of expansive rock masses under a high-humidity environment has become an urgent problem in deep underground expansive soft rock engineering, which needs to be solved.

Currently, researchers in China and other countries have obtained the tensile strength of rocks by using the direct stretching method and various indirect methods. In the direct tensile method, axial stretches are directly applied to a rock specimen, and the uniaxial tensile strength is defined as the ratio of the tensile force to the cross-sectional area of the specimen when the specimen fails. The direct method has been used rarely because of the difficulties in manufacturing the test piece and in ensuring that the axis of the test piece coincides with the direction of the load.15-17 Indirect experimental methods mainly include disk splitting, square plate fracturing, disk bending, and strip bending. Among them, the disk splitting method is the most widely used and has been recommended by the International Society for Rock Mechanics (ISRM) as the test method for the tensile strength of rocks.18,19

In recent years, researchers have investigated the tensile strength using the disk splitting method through experiments, theoretical analyses, and numerical simulations. In the experimental research, the factors influencing the tensile strength have been analyzed from different aspects such as the loading mode, pad size effect, and water-rock coupling. From the results of relevant studies employing, the splitting test, it was found that different loading modes could cause disparities in the stress distribution on a test piece, which greatly influence its failure load. The failure mechanism of a test piece varies with the type of loading mode.20,21 Moreover, the size of the loading pad can affect the tensile strength of a test piece. During the experiment, different pad sizes resulted in different contact angles in the loading process, causing differences in the load. Therefore, to ensure accuracy of the test result, it is necessary to determine the appropriate pad size.22,23 Yang et al24 showed that the hardness of the pad also influences the splitting tensile strength of rocks. The loading on a hard pad is equivalent to a point loading, whereas that on a soft pad is equivalent to a distributed loading because it is easily deformed.

Furthermore, water has a softening effect on rocks, and the water content can affect the tensile strength and failure characteristics of rock samples.25 In the theoretical studies, researchers have analyzed the characteristics of disk crust failure in three-dimensional coordinates and corrected errors in the disk tensile strength formula caused by the elastic plane hypothesis. From the results of the correlation analysis, the disk splitting stress distribution was related to the height-diameter ratio and Poisson’s ratio of the specimen. The maximum tensile stress of the specimen appeared at the center of the end face in three-dimensional coordinates.26-29 The results of the study by Kourkoulis and Markides showed that the contact mechanical behavior of the loading platform and the specimen has a great influence on the disk stress field and displacement field.30,31 In addition, based on the structural parameters and the water content of rocks, the strength deterioration law was investigated, and an evaluation method for the strength and deformation of rocks under a weakened action was proposed.32-35 Li and Wang described the water distribution in a sample based on two parameters, that is, critical degree of saturation and variation of saturation degree per unit length, which provides a new method for studying the weakening effect of water on rock strength.36 However, their indoor experiment was affected by various conditions and factors; thus, the obtained results cannot provide enough information. The theoretical analysis model is ideal, but the deduction process is extremely complicated. Therefore, numerical simulation has become an important element of the Brazilian splitting test. Researchers have proposed different numerical models to investigate the heterogeneity, precracks, microscopic parameters, and loading mode of rocks.37-41 Moreover, the influence of the maximum tensile strain criterion and the maximum tensile strength criterion on the crack initiation point position was also analyzed.32

To date, the rock expansion theory of the stress-strain field due to the water-rock interaction is based on specific expansion experimental models. The representative rock expansion theories include Gysel’s one-dimensional expansion theory and Wittke’s three-dimensional expansion theory.43,44 These theories are limited by experimental models. In fact, the range and degree of the rock mass affected by humidity are all changed. The expansion and softening of a rock mass after the action of water will cause changes in its stress-strain field and displacement field. The effect of humidity on a rock mass is similar to that of temperature. For this reason, some scholars have made an analogy between the humidity field and the temperature field. In detail, the constitutive relation due to the temperature change was replaced by a constitutive relation due to the expansion and softening of the rock exposed to water. The change field of temperature T caused by heat conduction was replaced by the change field of humidity H caused by water infiltration.45-47

From the above results, disk splitting is still the main method for testing the tensile strength of rocks. Researchers
in China and other countries have conducted theoretical, simulation, and experimental research from the aspects of contact mechanics behavior, size effect, and splitting failure mode. However, most of the results in these studies were obtained under the condition of a single load, while only a few studies examined the splitting failure mechanism under the combined action of a high-humidity environment and the stress environment of the expansive soft rock deep underground. Therefore, in this study, based on the theory of humidity stress field, an analytical solution of the disk splitting stress under a combined action of humidity diffusion and radial load was derived. In addition, the stress evolution law and splitting failure mechanism of the disk under the coupled action of the external humidity environment and stress environment were analyzed. Furthermore, a modified formula for the tensile strength of the Brazilian splitting test was proposed to enrich and develop the theory of rock mechanics deep underground.

2 | ANALYSIS OF DISK SPLITTING STRESS UNDER A COUPLED HUMIDITY-MECHANICAL ACTION

2.1 | Mechanical model

The expansive surrounding rock in a high-humidity environment deep underground is affected by humidity and excavation disturbance. As a result, the failure mechanism of the rock mass is different from that of a rock mass in shallow underground. After excavation of a roadway, the content of water in the soft rock area changes owing to the diffusion of water. Under the dual influence of the change in water content and the effect of disturbance, this part of the rock mass expands and softens, causing changes in the stress field and strain field of the surrounding rocks of the roadway. From the shallow to the deep part of the surrounding rock, the humidity distribution changes continuously. In other words, when the surrounding rock is affected by a certain water source (eg, humid air), a change in humidity (water content) occurs in the surrounding rock, which is controlled by the water diffusion, as shown in Figure 1.

To reveal the tensile fracture mechanism of the expansive surrounding rock under a combined action of the humidity field and mechanical field, a splitting model was established, as shown in Figure 2. Radial pressure is applied on the disk in a high-humidity environment. \( P, b, \) and \( t \) are the radial load, radius, and thickness of the disk, respectively. In the analysis, the following assumptions were made:

1. The disk is elastically deformed under the action of the force and humidity field. In addition, the humidity field and the mechanical field do not interact.

2. The distribution of the humidity field is axisymmetric, that is, the humidity distribution is only related to the radial coordinate \( r \).

3. The impact zone of the humidity field is \( a \leq r \leq b \). Here, \( a \) (a quantitative assumption) is the radius of the area not affected by humidity, which should be determined by the combination of the material properties and the external humidity gradient. However, the radius \( a \) is difficult to obtain; therefore, for a qualitative analysis, \( a \) is set as a constant.

2.2 | Splitting stress field of the disk under the coupled humidity-mechanical action

2.2.1 | Stress field of the disk under the action of humidity field

Currently, there is no mature theoretical system for the humidity field. Thus, some researchers have compared the humidity field with the temperature field and proposed to establish the theory of humidity stress field of rocks under the action of water (Miao et al 1993) by modifying the parameters in the temperature stress field theory. In detail, the constitutive relation due to the temperature change was replaced by the constitutive relation due to the expansion and softening of the rock exposed to water. The change field of temperature \( T \) caused by heat conduction was replaced by the change field of humidity \( H \) due to water infiltration. This theory was used in the following analysis.

Strictly speaking, the change in the humidity field of a rock mass is related to its internal structure, mineral composition, and stress field. The humidity field and stress field are coupled. With the increase in water content, most expansive rocks will exhibit the phenomenon of elastic modulus, strength decrease, Poisson’s ratio, and volume increase. To facilitate the investigation, we can simplify the problem of
the humidity stress field by the following assumptions: (a) There is no interaction between the humidity field and the mechanical field. The humidity field can be obtained first, followed by the stress field. (b) The mechanical properties of the rock mass in a certain range of water content remain unchanged, and the modulus of elasticity \( E \) and Poisson's ratio \( \nu \) are constant. (c) The stress-strain relationship obeys Hooke's law.

In Figure 3, the humidity field of the disk in the natural state is \( \omega_0 \) and the external humidity field is \( H_0 \). The diffusion of humidity into the interior of the disk can cause a change in water content. We assumed that the humidity field \( \omega \) is only a function of the position and is independent of time, that is, a constant humidity field is generated inside the disk. Thus, the variation in the humidity field caused by the change in water content can be expressed as follows:

\[
H(x,y,z) = \omega(x,y,z) - \omega_0
\]

According to the humidity diffusion equation, because there is no humidity source in the disk and the humidity field is independent of time, the above variable humidity field should satisfy the following equation:

\[
\nabla^2 H = 0
\]  
(2)

where \( \nabla^2 \) is a Laplacian operator, which can be expressed as

\[
\nabla^2 = \frac{d^2}{dr^2} + \frac{1}{r} \frac{d}{dr}
\]

in the plane with axial symmetry, and \( H \) is a function of the radial position \( r \).

\[
H = A \ln r + B
\]  
(3)

The humidity boundary conditions of the disk are \( (H)_{r=a} = 0 \) and \( (H)_{r=b} = H_0 \). After substituting the boundary conditions into Equation (3) to determine the constant parameters, the following equation can be obtained:

\[
H = H_0 \frac{\ln r - \ln a}{\ln b - \ln a} \quad (a \leq r \leq b)
\]

\[
H = 0 \quad (r \leq a)
\]

(4)

The above equation is the distribution function of the variable humidity field.

The equilibrium equation of the humidity stress field of the axisymmetric problem in the plane can be expressed as

\[
\frac{d\sigma_r}{dr} + \frac{1}{r} (\sigma_r - \sigma_\theta) = 0
\]

(5)

where \( \sigma_r \) is the radial stress and \( \sigma_\theta \) is the hoop stress.

The geometric equation is as follows:

\[
\varepsilon_r = \frac{d\varepsilon_r}{dr}, \varepsilon_\theta = \frac{\varepsilon_r}{r}
\]

(6)
where \( \varepsilon_r \) is the radial strain and \( \varepsilon_\theta \) is the hoop strain. The symbol \( u_r \) represents the radial displacement.

The physical equation is as follows:

\[
\varepsilon_r = \frac{1}{E} \left( \sigma_r - \nu \sigma_\theta \right) + \alpha H \\
\varepsilon_\theta = \frac{1}{E} \left( \sigma_\theta - \nu \sigma_r \right) + \alpha H \\
\gamma_{r\theta} = \frac{2(1+\nu)}{E} \tau_{r\theta}
\]

(7)

where \( E \) is the elastic modulus, \( \nu \) the Poisson’s ratio, \( \tau_{r\theta} \) the shear stress, \( \gamma_{r\theta} \) the shear strain, and \( H \) the humidity change function. The symbol \( \alpha \) refers to the linear expansion coefficient corresponding to the maximum expansion of rock mass under a certain water content. To simplify the problem, we considered that \( \alpha \) does not change with the change in humidity and it is necessary to treat \( \alpha \) as a constant in the solution of the stress-strain field.

We set the humidity stress function to \( \Phi (r) \). Then,

\[
\sigma_r = \frac{\Phi (r)}{r}, \sigma_\theta = \frac{d\Phi (r)}{dr}
\]

(8)

Apparently, the above stress expression can satisfy the requirement of Equation (5).

The strain obtained by Equation (6) should satisfy the following compatibility equation:

\[
\frac{d}{dr} \left( r \varepsilon_\theta \right) - \varepsilon_r = 0
\]

(9)

By substituting Equation (8) into Equation (7), the expression of strain using the humidity stress function can be obtained. Then, by substituting the expression of strain into Equation (9), the humidity stress function would satisfy the following equation:

\[
\frac{d}{dr} \left[ \frac{1}{r} \frac{d}{dr} (r \Phi) \right] = -aE \frac{dH}{dr}
\]

(10)

The general solution of the humidity stress function can be obtained by solving the above equation. The symbol \( \rho \) represents the radial position in the humidity-affected zone of the disk, \( a \leq \rho \leq r \).

\[
\Phi (r) = -aE \frac{1}{r} \int_a^r H \rho d\rho + D_1 r + \frac{D_2}{r}
\]

(11)

By substituting Equation (11) into Equation (8), the stress component can be obtained as follows:

\[
\sigma_r = -aE \frac{1}{r} \int_a^r H \rho d\rho + D_1 + \frac{D_2}{r^2}
\]

\[
\sigma_\theta = aE \left( -H + \frac{1}{r} \int_a^r H \rho d\rho \right) + D_1 - \frac{D_2}{r^2}
\]

(12)

where \( D_1 \) and \( D_2 \) are integral constants, which need to be solved using boundary conditions.

In this problem, there is no stress effect on the inner and outer boundaries of the variable humidity field; thus, the following equations are satisfied:

\[
(\sigma_r)_{r=a} = 0, (\sigma_r)_{r=b} = 0
\]

(13)

Equation (12) is substituted to Equation (13) to obtain the following solution:

\[
D_1 = \frac{aE}{b^2 - a^2} \int_a^b H \rho d\rho, D_2 = \frac{a^2 aE}{a^2 - b^2} \int_a^b H \rho d\rho
\]

(14)

Equations (4) and (14) are substituted into Equation (12) to obtain the expression of stress:

\[
\sigma_r^H = \frac{aE(1+2\nu)}{(1+\nu)^2} \frac{H_0}{2} \left[ -\ln \frac{b}{r} + \frac{a^2}{b^2 - a^2} \left( \frac{b^2}{r^2} - 1 \right) \ln \frac{b}{a} \right]
\]

\[
\sigma_\theta^H = \frac{aE(1+2\nu)}{(1+\nu)^2} \frac{H_0}{2} \left[ 1 - \ln \frac{b}{r} + \frac{a^2}{b^2 - a^2} \left( \frac{b^2}{r^2} + 1 \right) \ln \frac{b}{a} \right]
\]

(15)

where the superscript \( H \) in the stress symbol is used to distinguish the stress field caused by the variable humidity field from the stress caused by the load.

Using coordinate transformation, the stress component of the humidity stress field in the Cartesian coordinate system is obtained as follows:

\[
\sigma_x^H = \frac{\sigma_r^H + \sigma_\theta^H}{2} + \frac{\sigma_r^H - \sigma_\theta^H}{2} \frac{x^2 - y^2}{x^2 + y^2}
\]

\[
\sigma_y^H = \frac{\sigma_r^H + \sigma_\theta^H}{2} - \frac{\sigma_r^H - \sigma_\theta^H}{2} \frac{x^2 - y^2}{x^2 + y^2}
\]

\[
\sigma_{xy}^H = \left( \sigma_r^H - \sigma_\theta^H \right) \frac{xy}{x^2 + y^2}
\]

(16)

where

\[
\sigma_r^H + \sigma_\theta^H = \frac{aE(1+2\nu)}{(1+\nu)^2} \frac{H_0}{2} \left[ 1 - 2 \ln \frac{b}{r} - \frac{a^2}{b^2 - a^2} \ln \frac{b}{a} \right]
\]

\[
\sigma_r^H - \sigma_\theta^H = \frac{aE(1+2\nu)}{(1+\nu)^2} \frac{H_0}{2} \left[ 1 - 2 \ln \frac{b}{r} - \frac{a^2}{b^2 - a^2} \ln \frac{b}{a} \right]
\]

(17)

The stress expressed by polar coordinates in Equation (17) can also be changed accordingly.
2.2.2 | Analysis of disk stress under the action of radial load

In Figure 4, $P$, $d$, and $t$ are the concentrated force, diameter, and thickness of the disk, respectively.

To obtain the stress at any point of the disk under pressure, as indicated in Figure 5, the pressures at the upper and lower ends along the vertical diameter $O_1O_2$ are imposed by $P_1$ and $P_2$, respectively, (actually $P_1 = P_2 = P$). Then, a horizontal tangent line AA is drawn to pass the upper endpoint of the vertical diameter $O_1$. The part below AA is assumed to be a half-infinite plane, and the disk with a diameter of $d$ is cut out from the plane using $O_1$ as the starting point. Then, another horizontal tangent line BB is drawn to pass the lower endpoint $O_2$, and the part above BB is assumed to be a half-infinite plane. The disk with diameter $d$ is cut out from the plane using $O_2$ as the starting point, as shown in Figure 6.

According to Michell’s solution, the stress component at any point of the disk under the force at the upper end $P$ can be expressed as follows:

$$
\sigma'_r = -\frac{2p \cos \theta_1}{\pi t} \frac{r}{r_1}
$$

(18)

where $r_1$ and $\theta_1$ are respectively the polar radius and polar angle with point $O_1$ as the pole, and $p/t$ represents the force per unit of thickness. In particular, at any point $M$ on the periphery of the disk (as exhibited in Figure 7), because $r_1 = d \cos \theta_1$, the stress component can be expressed as follows:

$$
\sigma'_r = -\frac{2p}{\pi d t} \sigma'_0 = 0, \tau'_{r\theta} = 0
$$

(19)

Similarly, the stress component at any point in the disk under the force at the lower end $P$ can be expressed as

$$
\sigma''_r = -\frac{2p \cos \theta_2}{\pi t} \frac{r}{r_2}
$$

(20)

where $r_2$ and $\theta_2$ are the polar radius and polar angle, respectively, with $O_2$ as the pole. In particular, at any point $M$ on the periphery of the disk, since $r_2 = d \cos \theta_2$, the stress component can be expressed as

$$
\sigma''_r = -\frac{2p}{\pi d t} \sigma''_0 = 0, \tau''_{r\theta} = 0
$$

(21)

Thus, the disk shown in Figure 7 is subjected to a diametrical pressure at points $O_1$ and $O_2$, and a radial stress expressed as Equations (19) and (21) at any point on its circumference $M$. At point $M$, the compressive stresses in the directions of $r_1$ and $r_2$ are equal (see Figure 6). Moreover, $r_1$ and $r_2$ are perpendicular to each other, that is, $M$ is in the state with bidirectional uniform compressive stresses.
To facilitate the solution, a coordinate system $xoy$ was established and the center of the disk was used as the coordinate origin. The stresses along the direction of $OM$ and the direction perpendicular to $OM$ at the point $M$ are expressed as

$$
\sigma_x = \frac{\sigma_x + \sigma_y}{2} + \frac{\sigma_x - \sigma_y}{2} \cos 2\alpha - \tau_{xy} \sin 2\alpha = -\frac{2p}{\pi dt}
$$

$$
\sigma_y = \frac{\sigma_x - \sigma_y}{2} \sin 2\alpha + \tau_{xy} \cos 2\alpha = 0
$$

(22)

where the $x$ and $y$ directions are equivalent to the $r_1$ and $r_2$ directions. Owing to the arbitrariness of $M$, the above equation means that the cut disk in Figure 6 is subjected to a uniform normal stress in Equation (22) at the edge. The force diagram of the disk shown in Figure 6 is illustrated in Figure 7.

In fact, the periphery of the disk is a free boundary; therefore, the answer to the original question should be the superposition of the answers to the two figures below, as shown in Figure 8.

Based on the general solution of the axisymmetric stress problem and the finite value of the stress at the center of the circle, the stress distribution at any point on the disk under a uniform compressive stress can be obtained as follows:

$$
\sigma_x = \sigma_y = \frac{2p}{\pi dt}, \tau_{r\theta} = 0
$$

(23)

According to the coordinate transformation, the stress component at point $M$ in the $xoy$ plane can be obtained using the semi-infinite body model. The transformation diagram of the stress is depicted in Figure 9.

Based on the coordinate transformation and Equation (23), the stress on the disk in the Cartesian coordinate system is as follows:

$$
\sigma_x = \sigma'_x \sin^2 \theta_1 + \sigma''_x \sin^2 \theta_2 + \frac{2p}{\pi dt}
$$

$$
\sigma_y = \sigma'_x \cos^2 \theta_1 + \sigma''_x \cos^2 \theta_2 + \frac{2p}{\pi dt}
$$

$$
\tau_{xy} = -\sigma'_x \sin \theta_1 \cos \theta_1 + \sigma''_x \sin \theta_2 \cos \theta_2
$$

(24)

By substituting Equations (18) and (20) into the above formula, the following equation can be obtained:
\[
\sigma_x = -\frac{2p}{\pi t} \left( \frac{\cos \theta_1 \sin^2 \theta_1 + \cos \theta_2 \sin^2 \theta_2 - 1}{r_1} \right)
\]
\[
\sigma_y = -\frac{2p}{\pi t} \left( \frac{\cos^3 \theta_1 + \cos^3 \theta_2 - 1}{r_2} \right)
\]
\[
\tau_{xy} = \frac{2p}{\pi t} \left( \frac{\cos^2 \theta_1 \sin \theta_1 - \cos^2 \theta_2 \sin \theta_2}{r_1} \right)
\]

When point \( M \) is on the left side of the \( y \)-axis, the coordinate transformation diagram is presented in Figure 10.

According to the balance of the microelement, the following set of equations can be obtained:

\[
\sigma_z = \sigma'_z \sin^2 \theta_1 + \sigma''_z \sin^2 \theta_2 + \frac{2p}{\pi dt}
\]
\[
\sigma_r = \sigma'_r \cos^2 \theta_1 + \sigma''_r \cos^2 \theta_2 + \frac{2p}{\pi dt}
\]
\[
\tau_{r\theta} = \sigma'_r \sin \theta_1 \cos \theta_1 + \sigma''_r \sin \theta_2 \cos \theta_2
\]

Comparing Equations (24) and (26), the solution of the disk stress can be found in Equation (25). In Equation (25), the signs of \( \theta_1 \) and \( \theta_2 \) are positive when the calculated point is on the right side of the \( y \)-axis and negative when on the left side. From Figure 10, the following equation can be easily obtained:

\[
\sin \theta_1 = \frac{x}{r_1}, \cos \theta_1 = \frac{b-y}{r_1}
\]
\[
\sin \theta_2 = \frac{x}{r_2}, \cos \theta_2 = \frac{b+y}{r_2}
\]

By substituting the above equation into Equation (25), the following set of equations can be obtained:

\[
\sigma_x = \sigma'_x \left[ \frac{(b-y)x^2 + (b+y)x^2}{r_1^4} \right]
\]
\[
\sigma_y = \sigma'_y - \frac{2p}{\pi t} \left[ \frac{(b-y)^3 + (b+y)^3}{r_2^4} \right] - \frac{1}{d}
\]
\[
\tau_{xy} = \frac{2p}{\pi t} \left[ \frac{(b-y)^2 x - (b+y)^2 x}{r_2^4} \right]
\]

where

\[
r_1^2 = x^2 + (b-y)^2
\]
\[
r_2^2 = x^2 + (b+y)^2
\]

2.2.3 Analysis of disk stress under the combined action of humidity field and mechanical field

Considering the combined action of the humidity field and the external load \( P \), the stress at any point of the disk under both fields can be obtained as follows:

\[
\sigma_z = \sigma_z^p + \sigma_z^H
\]
\[
\sigma_r = \sigma_r^p + \sigma_r^H
\]
\[
\tau_{r\theta} = \tau_{r\theta}^p + \tau_{r\theta}^H
\]

where the stress components are expressed in Equations (16) and (28).

3 SPLITTING FAILURE MECHANISM OF THE DISK UNDER THE COUPLED HUMIDITY-MECHANICAL ACTION

3.1 Stress field of the disk under the coupled humidity-mechanical action

According to the results of laboratory tests, the disk parameters of the expansive mudstone are listed in Table 1. The data in Table 1 are used to study the stress field of the disk under the coupled humidity-mechanical action.

3.1.1 Humidity stress field of disk

Figure 11 displays the cloud diagrams of the horizontal expansive stress caused by the variable humidity field of the disk. Owing to the expansion of the rock mineral by water absorption, expansion and compression stress zones are developed under the influence of humidity, and a significant tensile stress concentration occurs at the dry-wet interface. In the area without the influence of humidity, the expansion stress is not observed under different humidity conditions. Within the humidity-affected zone, the horizontal tensile stress and compressive stress of the disk increase with the increase in external humidity. Before the rock encounters water, the cementation between the internal particles is stable and the structure is tight. After soaking, the volume of some clay particles expands and generates an expansion stress, which weakens the internal structure of the rock mass. The larger the expansion deformation of the rock under the influence of water, the stronger the corresponding expansion stress, resulting in changes in the disk stress distribution.

The distribution curves of the horizontal stresses at the radial and chordwise positions of the disk when the external humidity \( H_0 \) is 100% are presented in Figure 12. When \( x = 0 \), that is, the vertical radial position, the distribution curve of the horizontal stress exhibits an alternating change between compression and tension. The horizontal compressive stress zone appears in the region of \( r \geq 15.2 \) mm, whereas the tensile stress zone is in the region of \( 10 \) mm \( \leq r \leq 15.2 \) mm.
The maximum horizontal tensile stress is generated at the dry-wet interface. In the area unaffected by humidity, the horizontal stress is zero. The horizontal stress at \( x = 10 \) has the shape of a “double hump” and is significantly reduced compared to that at the radial position. In addition, the compressive stress zone at \( x = 10 \) is close to the center of the circle. Because the intersection of \( x = 10 \) and \( y = 0 \) is located in the dry-wet interface, the area inside this point is not affected by the humidity stress field; thus, the horizontal tensile stress is 0 in this area. At the chordwise position of \( x = 20 \), the horizontal stress curve has a trend of increasing first and then decreasing.

**FIGURE 9** Stress transformation of semi-infinite Brazilian splitting disk (\( M \) on the right side)

**FIGURE 10** Stress transformation of semi-infinite Brazilian splitting disk (\( M \) on the left side)

**TABLE 1** Disk parameters

| \( P \) (N) | \( b \) (mm) | \( t \) (mm) | \( a \) (mm) | \( \alpha \) (cm/cm%) | \( E \) (GPa) | \( \nu \) |
|---|---|---|---|---|---|---|
| 500 | 25 | 25 | 10 | \( 6e^{-4} \) | 2 | 0.25 |

**FIGURE 11** Horizontal stress cloud diagrams of the disk under various humidity conditions
Figure 13 illustrates the horizontal stress cloud diagrams of the disk at various humidity conditions under the coupled mechanical-humidity action. Owing to the end load, a compressive stress concentration zone is generated at the upper and lower ends of the disk. On the other hand, owing to the expansion of the soft rock mineral after the absorption of water, the disk is subjected to expansive and compressive stresses. As a result, a significant tensile stress concentration is generated at the dry-wet interface. In the region without the influence of humidity, no expansive stress is observed in the disk at different humidity conditions, and the evolution of horizontal stress in this region is only affected by the end load. Within the humidity-affected zone, the range and value of the disk horizontal stress concentration zone are affected by both the external humidity and the load, and they increase with the increase in external humidity. When the end load is constant, the increase in the humidity of the external environment can aggravate the expansion of the internal structure of soft rock after the absorption of water, causing an increase in the expansive stress.

The distribution curves of the horizontal stress of the disk at the radial and chordwise positions under the action of a single load and the coupled humidity-mechanical action when the external humidity is \( H_0 = 100\% \) are shown in Figure 14. Under the action of a single load, when \( x = 0 \), there is pressure at both ends and a uniform tensile stress is maintained in the middle. At \( x = 10 \), the horizontal stress in the chordwise direction is significantly smaller than that at the radial position. The distribution curve of the horizontal stress has the shape of a "single hump," and the peak point appears at \( y = 0 \). At \( x = 0 \), the horizontal stress distribution under the coupled humidity-mechanical action is different from that under a single load. Under the coupled humidity-mechanical action, the distribution of horizontal stress changes alternately between tension and compression. The horizontal compressive stress zone is located in the region of \( r \geq 21 \) mm, while the tensile stress zone is located in \( r < 21 \) mm. The maximum horizontal tensile stress is generated at the dry-wet interface. In the region without the influence of humidity, the horizontal stress is only affected by the load; thus, the horizontal stress curve coincides with the stress curve under a single load. At \( x = 10 \), the horizontal stress in the chordwise direction is significantly smaller than that at the radial position. In addition, the stress distribution curve in the chordwise direction exhibits a "double hump" shape. Because the intersection of \( x = 10 \) and \( y = 0 \) is located at the dry-wet interface, the area inside this point is not affected by the humidity stress field, and therefore, the horizontal tensile stress at this position is only affected by the end load, which is consistent with that under a single load.

The cloud diagrams of the vertical stresses of the disk at different humidity conditions under the coupled humidity-mechanical action are depicted in Figure 15. Owing to the end load, a vertical compressive stress concentration zone is generated at both ends of the load. In the area without the influence of humidity, the stress evolution of the disk under different humidity conditions is only affected by the load, and no expansive stress is generated in the disk. Within the humidity-affected zone, the range and value of the vertical stress concentration zone of the disk increase with the increase in external humidity.

Figure 16 shows the vertical stress distribution curves at the radial and chordwise positions of the disk when the external humidity is \( H_0 = 100\% \). When \( y = 0 \), the horizontal
The stress distribution exhibits an alternating change between tension and compression. The vertical tensile stress zone appears in the region of $9.5 \, \text{mm} \leq r \leq 12 \, \text{mm}$, while the compressive stress zone appears in other areas. The maximum vertical tensile stress is observed at the dry-wet interface. In the area without the influence of humidity, the vertical stress is only affected by the end load, and the distribution curve of the stress has an "upper concave" shape, which reaches the pit at the center of the disk. At $y = 10$, the vertical stress curve exhibits a tendency of an alternating increase and decrease, and the maximum point of compressive stress appears at the intersection of $y = 10$ and $x = 0$. At $y = 20$, the trend of the vertical stress curve is similar to that at $y = 10$. Because the position of $y = 20$ is far from the vertical tensile stress zone, the impact of the tensile stress is small; thus, the rise phase of the curve is not obvious. From the figure, the vertical stress curves at the positions $y = 0$, 10, and 20 exhibit a similar trend, that is, the compressive stress reaches a maximum in the loading direction and is greater at the position closer to the loading point.

### 3.2 Influence of rock material properties on the evolution of stress field

The influence of rock material properties on the disk stress evolution was investigated from two aspects: rock elastic modulus and linear expansion coefficient. The specific parameters are listed in Table 2.

#### 3.2.1 Stress field of the disk at different elastic moduli

The basic parameters of the disk in Table 2 remain unchanged, and we analyzed the stress evolution law of the disk under the coupled humidity-mechanical action when the linear expansion coefficient $\alpha$ is $6 \times 10^{-4}$ and the elastic moduli are 2 GPa, 5 GPa, and 8 GPa, respectively. Figure 17 shows the cloud diagrams of the horizontal stresses in the disk at different elastic moduli under the coupled humidity-mechanical action. Under the condition that both the external load and the humidity field are unchanged, the evolution trends of the stress of the disk at different elastic moduli are almost the same. The horizontal compressive stress concentration zones are generated at both ends of the disk loading. The soft rock minerals are expanded by the absorption of water, which causes expansive and compressive stress zones in the disk. In addition, a significant tensile stress concentration occurs at the dry-wet interface. In the area without the influence of humidity, the stress evolution of the disk at different elastic moduli is only affected by the end load, and no expansive stress is generated. Within the humidity-affected zone, the value and gradient of the horizontal stress in the disk increase with an increase in the elastic modulus. Under the same
deformation, the expansive stress generated by the rock increases with an increase in the elastic modulus.

The distribution curves of the horizontal stresses at the radial and chordwise positions of the disk at three different elastic moduli are presented in Figure 18. At $x = 0$, which is the vertical radial position, the distribution curve of the horizontal stress for the three elastic moduli exhibits an alternating change between compression and tension. The peak value of the horizontal tensile stress appears at the dry-wet interface. In addition, with an increase in the elastic modulus, the peak value of the horizontal tensile stress also increases. When $E = 2 \times 10^9$, the horizontal compressive stress zone appears in the region of $r \geq 21$ mm, whereas the tensile stress zone appears in the region of $r < 21$ mm. When $E = 5 \times 10^9$, the horizontal compressive stress zone appears in the region of $r \geq 18$ mm, while the tensile stress zone appears in the region of $r < 18$ mm. When $E = 8 \times 10^9$, the horizontal compressive stress zone appears in the region of $r \geq 17$ mm, and the tensile stress zone appears in the region of $r < 17$ mm. As the elastic modulus increases, the horizontal compressive stress zone gradually approaches the center of the disk. In the area without the influence of humidity, the evolution of stress is only affected by the end load, and thus, the curves of the horizontal stress under the three conditions coincide with each other.

### 3.2.2 Stress field of the disk at different values of expansion coefficient

Deep expansive soft rocks are easily softened and expanded under the action of groundwater or a high-humidity environment, which in turn generates a large expansive stress and has a considerable impact on the tensile strength. By keeping the basic parameters of the disk described in Table 2 unchanged, we analyzed the stress evolution law of the disk under the coupled humidity-mechanical action when the elastic modulus $E$ is 2 GPa and the coefficients of linear expansion are $2 \times 10^{-4}$, $6 \times 10^{-4}$, and $1 \times 10^{-3}$, respectively. Figure 19 presents the cloud diagrams of the horizontal stresses of the disk obtained at different expansion coefficients under the coupled humidity-mechanical action. In the area without the influence of the diffusion of humidity, the disk with different expansion properties is only affected by the end load, and no expansive stress is generated. Within the humidity-affected zone, the range and value of the horizontal stress concentration zone of the disk increase with an increase in the linear expansion coefficient. As the linear

### Table 2 Disk parameters under different rock properties

| $E$ (GPa) | $\alpha$ (cm/cm/%) | $P$ (N) | $b$ (mm) | $t$ (mm) | $a$ (mm) | $\nu$ | $H_0$ (%) |
|-----------|-------------------|--------|----------|----------|---------|-----|-----------|
| 2         | $2 \times 10^{-4}$| 500    | 25       | 25       | 10      | 0.25| 100       |
| 5         | $6 \times 10^{-4}$|        |          |          |         |     |           |
| 8         | $1 \times 10^{-3}$|        |          |          |         |     |           |

### Figure 16 Vertical stress curves of the disk under the coupled humidity-mechanical action ($H_0 = 100\%$)

### Figure 17 Horizontal stress cloud diagrams of the disk at various elastic moduli under the coupled humidity-mechanical action
expansion coefficient increases, the expansion and deformation of the internal structure of the soft rock due to the influence of water become more severe, causing a greater expansive stress.

Figure 20 exhibits the distribution curves of the horizontal stress at the radial and chordwise positions of the disk under three different linear expansion coefficients. At \( x = 0 \), which is the vertical radial position, all distribution curves of the horizontal stresses under the three linear expansion coefficients show an alternating change between compression and tension. The peak of the horizontal tensile stress appears at the dry-wet interface and increases with an increase in the linear expansion coefficient. When \( \alpha = 2 \times 10^{-4} \), the horizontal compressive stress zone appears in the region of \( r \geq 24 \text{ mm} \), while the tensile stress zone appears in the region of \( r < 24 \text{ mm} \). When \( \alpha = 6 \times 10^{-4} \), the horizontal compressive stress zone and tensile stress zone appear in the regions of \( r \geq 22 \text{ mm} \) and \( r < 22 \text{ mm} \), respectively. When \( \alpha = 1 \times 10^{-3} \), the horizontal compressive stress zone appears in the region of \( r \geq 19 \text{ mm} \), and the tensile stress zone appears in the region of \( r < 19 \text{ mm} \). With the increase in the linear expansion coefficient, the horizontal compressive stress zone gradually approaches the center of the disk. In the area without the influence of humidity, the evolution of the stress in the disk is only affected by the end load; thus, the curves of the horizontal stress under the three different conditions overlap.

4 | ANALYSIS OF THE MECHANISM OF DISK SPLITTING FAILURE

4.1 | Disk splitting failure characteristics under the coupled humidity-mechanical action

To compare the stress distribution of the disk caused by the diffusion of humidity, the cloud diagrams of the splitting stress of the disk under a single load are shown in Figure 21. Owing to the end load, stress concentration zones are generated at the upper and lower ends of the disk. It can be observed from Figure 21A that a horizontal compressive stress concentration zone is generated in the loading region at the end of the disk. The horizontal tensile stress of the disk reaches its maximum along the loading direction and decreases as the position of \( x \) moves toward the ends. From Figure 21B, it can be seen that a vertical compressive stress concentration zone is generated at both ends of the loading. In the loading direction, the vertical compressive stress is greater than the horizontal one. At the center of the disk, the compressive stress is the smallest in the loading direction, and the value of the compressive stress gradually increases as the position of \( y \) shifts toward the loading end.

Under the action of a single load, the distribution of the horizontal stress on the disk along the radial loading line exhibits the following trend: Both ends are compressed and the middle region has a constant maximum horizontal tensile stress. From the two ends to the center of the disk, the vertical compressive stress gradually decreases. At the center of the disk, the compressive stress is approximately 3 times larger than the tensile stress. According to Griffith’s strength theory, in the splitting test of an expansive soft rock, the tensile strength at the center of a rock specimen reaches the limit value first. Thus, the

![Figure 18](image1)

**Figure 18** Horizontal stress curves of the disk at various elastic moduli under the coupled humidity-mechanical action \((x = 0)\)

![Figure 19](image2)

**Figure 19** Horizontal stress cloud diagrams of the disk at different linear expansion coefficients
crack starts from the center of the disk, and then develops and expands toward both loading ends. From the previous analysis, the distribution of the horizontal stress under the coupled humidity-mechanical action is different from that under a single load. Owing to the influence of the humidity field, the distribution of the horizontal stress along the loading line exhibits an alternating change between tension and compression. Moreover, the maximum horizontal tensile stress is generated at the dry-wet interface. As \( x \) moves toward both ends, the horizontal stress is significantly reduced. The compressive stresses gradually increases from the center of the disk toward both loading ends. Under the coupled humidity-mechanical action, the failure point of the specimen is transferred from the center of the disk to the intersection of the dry-wet interface and the loading direction. Furthermore, owing to the influence of the loading and diffusion of humidity, the crack of the disk develops and expands from the dry-wet interface to the loading ends. Consequently, the splitting failure of the disk under the coupled humidity-mechanical action exhibits a completely different characteristic from that under a single load.

### 4.2 Modified formula for splitting failure under the coupled humidity-mechanical action

Based on the above analysis, under the coupled humidity-mechanical action, the fracture of the disk does not start from the center. Thus, the formula for the splitting tensile strength \( \sigma_i = -2p/\pi dt \) under a single load is not applicable and needs to be modified. The modified stress field of the disk under the coupled humidity-mechanical action is defined as follows:

\[
\begin{align*}
\sigma_x &= \lambda_x \sigma_x^p \\
\sigma_y &= \lambda_y \sigma_y^p \\
\tau_{xy} &= \lambda_{xy} \tau_{xy}^p
\end{align*}
\]  

(30)

From Equation (16), (17), and (28), the modification coefficient can be expressed as follows:

\[
\begin{align*}
\lambda_x &= 1 + \frac{\sigma_x^H}{\sigma_x^p} = 1 + \frac{\sigma_x^H - \sigma_x^p}{\sigma_x^p} \\
\lambda_y &= 1 + \frac{\sigma_y^H}{\sigma_y^p} = 1 + \frac{\sigma_y^H - \sigma_y^p}{\sigma_y^p} \\
\lambda_{xy} &= 1 + \frac{\tau_{xy}^H}{\tau_{xy}^p} = 1 + \frac{\tau_{xy}^H - \tau_{xy}^p}{\tau_{xy}^p}
\end{align*}
\]  

(31)

Under the coupled humidity-mechanical action, the failure point of the disk is at the intersection of the loading direction and the dry-wet interface, that is, when \( x = 0 \) and \( y = a \). The maximum tensile stress is generated in the disk, which can be described as follows:

\[
\sigma_x^p = \frac{-2p}{\pi t} \left[ \frac{(b-y) x^2}{r_1^4} + \frac{(b+y) x^2}{r_2^4} - \frac{1}{d} \right] = \frac{2p}{\pi t d}
\]

\[
\begin{align*}
\sigma_x^H + \sigma_y^H &= -\frac{\alpha E(1+2\nu) H_0}{(1+\nu)^2} 2 \ln \frac{a}{b} \left[ 1 - 2 \frac{b^2}{b^2 - a^2} \ln \frac{b}{a} \right] \\
\sigma_x^H - \sigma_y^H &= -\frac{\alpha E(1+2\nu) H_0}{(1+\nu)^2} 2 \ln \frac{a}{b} \left[ 2 \frac{b^2}{b^2 - a^2} \ln \frac{b}{a} - 1 \right]
\end{align*}
\]  

(32)

By substituting the above equation into Equation (31), the calculation formula for the splitting strength of the disk under the coupled humidity-mechanical action can be obtained as follows:

\[
\sigma_i^{H-P} = \lambda \sigma_i^p
\]  

(33)

where \( \sigma_i^{H-P} \) and \( \sigma_i^p \) are the splitting strengths of the disk under the coupled humidity-mechanical effect and the single load, respectively. The correction factor \( \lambda \) can be expressed as

\[
\lambda = 1 + \frac{\pi d a E (1+2\nu) H_0 \left[ \frac{3b^2}{b^2 - a^2} \ln \frac{b}{a} - 1 \right]}{4p (1+\nu)^2 \ln \frac{b}{a}}
\]  

(34)
Therefore, in a high-humidity environment, the splitting strength of an expansive soft rock is related to the humidity field, elastic modulus of the rock mass, Poisson’s ratio, and coefficient of linear expansion.

5 | CONCLUSIONS

To investigate the tensile failure of expansive soft rocks under a high-humidity environment deep underground, a calculation model of disk splitting under a high-humidity field was proposed. The analytical expression for the stress of a disk under a coupled humidity-mechanical action, the evolution law of the stress field with the change in physical parameters, and the splitting mechanism were analyzed in detail. Moreover, a modified formula was proposed to calculate the splitting strength. The main conclusions are as follows:

1. Under different humidity conditions and different lithologies, the stress field of the disk is always concentrated at the dry-wet interface. In addition, the range and value of the stress concentration zone increase with the increase in the humidity of the external environment, elastic modulus of soft rock, and linear expansion coefficient. The influence of the humidity in the external environment on the splitting damage of the disk is not negligible.

2. The stress evolution of the disk under the coupled humidity-mechanical action is completely different from that under the single-load action. The horizontal tensile stress of the disk reaches its maximum at the intersection of the loading line and the dry-wet interface. The tensile-compressive stress ratio at this position also reaches the maximum value, that is, approximately 1:1, which is higher than that under a single load. Therefore, the failure point of the disk under the coupled humidity-mechanical action is transferred from the center to this position.

3. Under the coupled humidity-mechanical action, the position of the fracture failure point shifts from the center of the disk; thus, the corresponding calculation formula of the splitting strength needs to be corrected. The modified formula shows that the splitting tensile strength of the disk under the coupled action is highly correlated with the diffusion law of the humidity field, range of influence, and physical parameters such as the elastic modulus and linear expansion coefficient of the rock.

4. The analytical results and modified formulas in this study can provide theoretical guidance for revealing the tensile failure of surrounding rock in a high-humidity environment. However, in the derivation process of the analytical solution in this study, neither the interaction effect of the humidity field and the mechanical field nor the deterioration of the petrophysical parameters caused by humidity diffusion was considered. In our next study, these parameters will be comprehensively taken into consideration.

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CONFLICT OF INTEREST

The authors have no conflicts of interest to declare.

DATA AVAILABILITY STATEMENT

The calculation data used to support the findings of this study are included in the article.

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