Interaction between soft rocks and water and its application to engineering

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Abstract. The interaction between soft rocks and water is a frontal project in the field of geotechnical engineering. This study constructs a time-effect model on the interaction between soft rocks and water by experimenting on the interaction and physical-mechanic of soft rocks, such as silty mudstone, argillaceous siltstone, and carbonaceous mudstone, which are sampled from a water supply project in South China. It also investigates the chemical mechanism of softening when soft rocks interact with water. Thus, the study not only builds a foundation for the theme of water–rock interaction but also provides effective guidance for the construction of priority projects.

Key words. soft rocks; experimental research; softening mechanism

1. Introduction
The characteristics of soft rocks shown are under strength, great deformation, better water affinity, and liability to weathering. Taking foundation settlement and slope failure for example, these characteristics threaten the potential construction and operation of projects; some of these characteristics even affect projects directly. Specifically, special soft rocks act unbroken, stiffness and good mechanical property in nature but get expansion, disintegration and softening in a short time while meeting water. Furthermore, the mechanical property’s decreasing by wide margin make it more roughly to the project.

For decades, research on water–rock interaction has focused on the analysis of the rock mass hydraulic and mechanical [12, 13, 14] coupling of seepage and deformation field models [1, 2, 3, 4]. Oda [15] rectified the law of cube, which only describes the seepage characteristic on the smooth fractured surface of single rock through the roughness of rock mass fissure. On this basis, the unit discharge of rough single fissures is set up. Yang Taihua [16] conducted an analog experiment on single-fissured seepage and studied the seepage rule on the irregular deformation of closed fissures. Yang Yanyi et al. [17] constructed a seepage–damage analysis coupling model of rock mass fissure and applied it to projects in practice.

With the increasing number of in-depth research on water–rock interaction and related topics, people have realized that the role water plays on rocks cannot be just considered by the effective stress principle simply but also by a complicated stress corrosion process. Colback et al. [7] investigated how water acts on the characteristics of rocks (e.g., intensity and deformation). Feucht [18] explored how chemical activity fluids act on the coefficient of friction of sandstone. Tang Liansheng [11] studied the mechanical and environmental domino effects of a few common sedimentary rocks in...
accordance with the chemical response of water to rock and soil. Yan [19] probed into the role that variety of dynamic parameter which water-saturation time played on by experimentation. In summary, it turns into the stage [20] that water & rocks’ mechanical and chemical actions are researched on deformational destruction of commonly fissured rock mass. However, it still thinks much of the interaction between water and soft rocks which play an important role on the stability of projects. Although targets and objects are unclear in the existing research, only in mine exploitation and aisle support design that soft rocks are considered more [21] nowadays. Based on the Water Supply Reconstruction Project from Dongjiang to Shenzhen (WSRPDS) in Guangdong Province, this study selects soft rocks, such as silty mudstone, carbonaceous mudstone, and argillaceous siltstone, which are distributed widely in the project, as research objects. According to a series of physical, chemical, and mechanical experimental research on rock softening while meeting water, this study further discusses the softening mechanism of rocks, thereby contributing to the literature on soft rock–water interaction.

2. Distribution and basic characteristics of soft rocks in the WSRPDS

The soft rocks along the WSRPDS mainly include silty mudstone, carbonaceous mudstone, and argillaceous siltstone. On the basis of geotechnical engineering reconnaissance reports, an engineering regional geological map (Figure 1) and a distribution map of three representative soft rocks along the WSRPDS (Figure 2) are taken out in accordance with research and synthetic analysis. The basic disciplinarian of distribution is displayed as follows:

2.1. Silty mudstone

Silty mudstones basset mainly in the layer of the Tangxia Group, Middle Jurassic and are distributed along the line of the project’s field adjoining Jinhu District from Shi Hill to Tangxia, neighborhood of Guangyin hill tunnel. The rock samples studied are collected from the upper subgroup (J₂t₃) of the sedimentation rock of the Tangxia Group, Middle Jurassic System in the Jinhu water pump station. The attitude of rocks is N40–45W/NE ∠35–40°. No fractured structure crosses around the district. These rocks mass basset on the slopes along both sides of the pump station, which is 14–38 m thick.

2.2. Carbonaceous mudstone

Carbonaceous mudstones basset mainly in the layer of the measured water segment 112 (C₁dc) in the lower Carboniferous and present a thin intercalation. The soft rocks studied are samples from the BIII2 slope, which presents a lenticular ore body.

2.3 Argillaceous silty fine stone

Argillaceous silty fine stones basset mainly in the layer of the Tangxia group (J₂t), Middle Jurassic; Jinji Fm (J₁j), Lower Jurassic; Xiaopin Fm (T₃x), Upper Triassic; and measured water segment (C₁dc), Lower Carboniferous. These stones are distributed around Qiaotou, Sima, Qilin, Zhangmutou, and the eastern Yantian Water Reservoir. Furthermore, these stones are present across layers with other kinds of rocks.

2.4. Strongly weathered argillaceous siltstone

Strongly weathered argillaceous siltstones basset mainly in the layer of the Tangxia group (J₂t), Middle Jurassic; Jinji Fm (J₁j), Lower Jurassic; and Xiaopin Fm (T₃x), Upper Triassic. These stones are distributed around Qilin, Zoumagang Tunnel, Qiaotou, and the eastern Yantian Water Reservoir. Furthermore, these stones are present across layers with sandstones and mudstones. The rock samples studied are collected from the sedimentation rock of Xiaopin Fm (T₃x), Upper Triassic in the Qilin aqueduct. The attitude of rocks is N80W–80E/NE(NW) ∠10–20°. These stones present inconformity contact with metamorphic rocks from the lower Sinian system and seem to have a flabby contact surface, complex contact boundary, and varied attitude. The strongly weathered layer is 2.5–28.0 m thick.
2.5. Mudstone
Mudstones basset mainly in the layer of the Tangxia Group (J$_2$) and upper subgroup (J$_2^b$), Middle Jurassic and Xiaopin Fm (T$_3x$), Upper Triassic and are distributed around Tangxia, Qiaotou, Qilin, and the eastern Yantian Water Reservoir. These stones present intercalation.

Figure 1. Regional geological map of the Dongshen Water Supply Reconstruction Project
3. Designing the experimental scheme for the interaction between soft rocks and water
The experiment is designed to obtain a disciplinarian, which describes how the physical and chemical reactions of rocks and its transformation influence the rocks’ structural, compositional, and mechanical properties. The experiment also aims to reveal the softening mechanism of rocks and identify the relationship between the law of the mechanical interaction of soft rocks and the compositional structure in all kinds of soft rocks while they are saturated. The designed experimental scheme is presented in Figure 3.
To reflect the practical condition of the interaction between soft rocks and water, rock samples were collected from the engineering site of the Donggai Project, and the water samples in which the rocks are to be immersed were obtained locally from relevant reaches along the constructional line within the drainage area of the Shima River.
Figure 3. Structural, compositional, and mechanical properties and transformation laws of soft rocks

The detailed steps of the scheme shown in Figure 3 are as follows: The soft rock samples were first cut into $30 \times 30 \times 30$ cm blocks. Then, the samples were placed in a $60 \times 42 \times 46$ cm glass sheet-covered plastic box. Afterward, natural water from the Dongjiang River was added until the water was 10 cm higher than the rock. After different soaking times, samples were taken to measure the rock’s structural, compositional, physical, and mechanical properties by using different instruments. Lastly, data were recorded.

4. Law of character changing on soft rocks after interaction with water

4.1. Law of physical character changing on soft rocks while interacting with water

4.1.1. Changing law of moisture capacity according to water-saturation period. The results of the experiments are shown in Figure 4. As shown in the figure, moisture capacity changes in accordance with the water-saturation period on silty mudstone; this result is consistent with the law, except for some curve points, which are due to asymmetrical sample distribution. The moisture capacity extent highly ranges first month to the third one while going to easy curve over three month and come down to a stable value C. The curve discussed above is fitting by exponential equation.
Light-yellow silty mudstone: \[ \omega = 35.318\exp(-0.724/t) \] (1)

Hoary silty mudstone: \[ \omega = 27.641\exp(-0.6176/t) \] (2)

The above phenomenon results from the high clay content, tiny pores, and dense distribution of silty mudstones. Thus, pore spaces are first filled with water, and then the setting produces a thick bound-watercourse surrounding clay particle during water saturation, thus thickening the weak bound-watercourse to heighten moisture capacity. Nevertheless, the tiny pores are full of water after three months, and the bound water course is thick enough to neutralize the electric charge on the surface of the clay particles. The increase rate of water content slows down, and weakly bound water attains saturation condition with time. Therefore, the moisture capacity stabilizes at a certain time.

Silty mudstones with three different colors were obtained from the Jinhu water pump station, whereas strongly weathered argillaceous siltstones were collected from the Qilin aqueduct. Figure 4 also shows that the moisture capacity of strongly weathered argillaceous siltstones changes as propinquity exponent law in a small scope. What is caused by high coarse grain content, great pore and sparse distributed of argillaceous siltstone. The pore is naturally filled with water to a certain degree; thus, the space where water could be held is limited in saturation setting. Moreover, this kind of soft rock contains a few clay particles to bind water. As a result, the moisture capacity increasing in water-saturation condition takes on gradual change law to a little extent instead of marked.

In accordance with the above discussion, the following conclusions can be drawn:

1. The change of the moisture capacity of silty mudstones and argillaceous siltstones generally follow the exponential law after water saturation not only because of high clay content but also because of the characteristics and distribution of the pores.

2. When clay content is high, the moisture capacity of soft rocks remarkably increases in the first three months; afterward, the increase rate slows down.

![Figure 4](image_url)

**Figure 4.** Observed curve of moisture capacity change on different soft rocks at different water saturation periods

### 4.1.2. Variation law on wet density with water-saturation time

An experiment curve of wet density on different soft rocks at different water-saturation periods is shown in Figure 5. Some values of wet density on soft rocks appear out of the way, which are falling as water saturation prolonging in a whole.
Figure 5. Experiment curve of wet density on different soft rocks at different water saturation periods

The above phenomenon results from the presence of abundant clay minerals, such as kaolinite and montmorillonite, in the soft rocks. During water saturation, clay minerals expand to aggrandize the volume of soft rocks, thus increasing water content. Moreover, the water in the pores of soft rocks is so much that it become part of the rocks. Furthermore, the density of water is far less than that of rocks. Thus, the weight of soft rocks is lessened responsibly to the same volume one which is full of rock only.

4.2. Variation law of microstructure on the interaction between soft rocks and water

4.2.1. Characteristics of microstructure on soft rocks at different water-saturation periods. To summarize the changing law of microstructure on saturated soft rocks, several experiments were conducted on soft rocks at different water-saturation periods via scanning electron microscopy (SEM). Figure 6 shows the microstructure of silty mudstones at different water-saturation periods. Through comparison and analysis, the characteristic changes of the microstructure of soft rocks after different water-saturation periods can be summarized as follows:

One month: Large holes of good connectivity are filled with water and overspread to aggrandize porosity but maintain structural shape.

Three months: Biggish holes are full of water and overspread to connect the bigger holes. The hole shapes turn from a primary strip and an irregular polygon into a slot and an ellipse. The connections among grains loosen even though the modes have been influenced.

Six months: In addition to the big holes with good connectivity, the tiny pores with poor connectivity become saturated with water and then expand. Hole gross decreases, whereas the total area increases, and the shape becomes round. The array modes of connection also change remarkably and seem to transform partially into loosened structures.

One year: The structure has transformed from a relatively compact one into a loose and porous one. High porosity is observed, and pores are equally distributed among grains. The connection between grains is mostly border–border or border–angle. Conformations are remodeled partly for chemical diversification. In addition, the structures appear to have transformed from relatively compact and highly intensive stripped or granular ones into loosened and porous cloddy or clover-leaf ones.

4.2.2. Variation law of microstructure on soft rocks after different water-saturation periods. Pore characteristics, including size, distribution, array, and connectivity, are important symbols of various microstructures. This study takes the fractal dimension $D_p$ of pore distribution as a fixed-quantity descriptive index of microstructures in soft rocks. The picture taken by SEM with $1\times1000$
unanimously is transacted by computer. Moreover, Sandbox \cite{17} of fractal theory is used to round off the pore-distributed fractal dimension $D_p$.

(1) Soft rocks composed of granular structures (rock samples from hoary silty mudstones)

The variation curve of the fractal dimension $D_p$ of the pore distribution of granular soft rocks are shown in Figure 7. The value of $D_p$ increases by degree with saturation time, which trend to be celerity especially six months later.
Figure 6. Variations in the regularity of the microstructures of soft rocks in their natural state and that after different saturation periods: (a–e) Changes of the microstructure of hoary silty mudstone from its natural granular structure to after 1 month, 3 months, 6 months, and 1 year of saturation; (f–j) Changes of the microstructure of light-yellow silty mudstone from its natural thickly stripped structure to after 1 month, 3 months, 6 months, and 1 year of saturation.

Figure 7. Variation curve of the fractal dimension of the pore distribution of granular structures.

Figure 8. Variation curve of the fractal dimension of the pore distribution of compact, bended structures.

Through analysis of the experiment data, a fitting equation can be obtained as follows:

\[ D_p = 0.0044t^2 - 0.0263t + 1.9839 \]

(3)

(2) Soft rocks composed of thickly stripped structures (rock samples from light-yellow silty mudstone)
The variation curve of the fractal dimension \( D_p \) of the pore distribution of thickly stripped soft rocks is shown in Figure 8. The value of \( D_p \) decreases in the first 6 months of water saturation. Then, \( D_p \) immediately increases.
The fitting equation of \( D_p \) and water-saturation time is as follows:

\[ D_p = 0.0017t^2 - 0.0137t + 1.987 \]

(4)

In summary, a period of 6 months is the critical point at which the fractal dimension \( D_p \) of the pore distribution of soft rocks in water-saturation state increases substantially. Therefore, the mechanical characteristics of soft rocks remarkably deteriorate because the microstructure loosens after 6 months of water saturation.

4.3 Method to identify the mineral composition of soft rocks

This section introduces various methods to identify the mineral composition of soft rocks.

(1) Using the slice lens of a polarizing microscope: Qualitative analysis is performed on the mineral composition of different types of rocks, and the composite content is estimated via rounding off.

(2) X-ray power diffraction analysis: Clay minerals, which are difficult to identify under the microscope, can be estimated through the peak value of diffraction; this value can be approximately converted to comparative content. This study aims to obtain the changing rules of the mineral composition of soft rocks at different water-saturation periods and how these rules affect the softening mechanism of rocks. However, the rules in the current experiment setting are difficult to obtain due to...
current testing measures and limited analysis precision. As a result, the research emphasizes compositional analysis by these means. For example, hoary silty mudstones are composed of quartz, sericite, montmorillonite, kaolinite, and illite; light-yellow silty mudstones comprise quartz, illite, kaolinite, and sericite.

4.4. Evolutionary regularity on the pH value of aqueous solutions and chemical composition with time after the interaction of soft rocks with water

4.4.1. pH value of aqueous solution at different saturation states of soft rocks. The soft rock samples were dipped in water from Dongjiang. The pH value is 7.33, which lies between the neutral zone and weak alkalinity. The values of the water take on moving after water saturation (Table 1). The pH value of the water surrounding silty mudstones increases to 46.1%, whereas that of argillaceous siltstones decreases to 10.5%.

This phenomenon occurs because soft rocks undergo chemical interactions, such as hydrolysis and ion exchanges, with the aqueous solution. First, the actions to rocks of compact structure occur on the surface layer and then inside for time lasting long. Therefore, the pH value of aqueous solution ranges little within the beginning water-saturation time. However, the seepage reduces the hours of these actions to the whole rock mass of incompact structure. Thus, the pH value of the aqueous solution remarkably varies in a short period

Table 1. Average pH values of the aqueous solution at different saturation states of soft rocks

| Water-saturation time (m) | Silty mudstone | Strongly weathered argillaceous siltstone |
|--------------------------|----------------|------------------------------------------|
| 0                        | 7.33           | 7.33                                     |
| 1                        | 6.05           | 7.15                                     |
| 3                        | 4.23           | 6.75                                     |
| 6                        | 3.95           | 6.56                                     |

4.4.2. Variation law of ion concentration in an aqueous solution on soft rocks at different water-saturation periods

1) Variation law of ion concentration in an aqueous solution on light-yellow silty mudstone

The variation curves of anion and cation concentrations in an aqueous solution on light-yellow silty mudstone are shown in Figures 9 and 10, respectively.

A) Anion

Most anion concentrations, except that of Cl$-$ in an aqueous solution, attenuate trending as exponent with time. The chemical actions between water and rocks in the first month of saturation are adsorption and dissolution. For instance, the minerals in rocks adsorb the ions of the aqueous solution after water saturation. Moreover, soluble minerals in the rocks begin to dissolve. The number of ions produced via dissolution is much lesser than that by adsorption. Thus, the ion concentration in the aqueous solution remarkably decreases. The actions of adsorption and dissolution between rocks and water are weakened within 3 months partly due to selective adsorption. Adsorption and dissolution level off within 3 months to stabilize SO$_4^{2-}$ and NO$_3^-$ concentrations. What the concentration of Cl$-$ mount up a little account for is there are still Cl$-$ coming out from the rocks.

Most ion concentrations, except that of Cl$-$, slightly change between 3 months and 1 year. The curves of all the concentrations tend to be plane, indicating that the chemical actions between water and rocks reach equilibrium that mineral dissolution counterpoises chemical precipitation. The fitting equation of the relationship between representative anion concentration and saturation time is as follows:

$$\text{NO}_3^{-}: y = 0.443\exp(1.12/t), \quad (5)$$
SO$_4^{2-}$: $y = 3.496\exp(0.98/t)$. \hspace{1cm} (6)

B) Cation
Most cation concentrations, except that of Na$^+$ at the third month in aqueous solution, attenuate trending as exponent well. One or two discrete points are likely to be worked by sampling error. The ion exchange between rocks and aqueous solution, especially that of Na$^+$ and Ca$^{2+}$, acts strongly in the first three months. Then, the ion concentrations level off. Some ions, such as Mg$^{2+}$, Fe$^{3+}$, Al$^{3+}$, and Si$^{4+}$, are the main components of infusible minerals. The ions that seldom hydrolyze and exchange in aqueous solutions usually exist as stable compounds. Thus, the curves of these concentrations do not move too much with time.

The actions of hydrolysis and exchange are weakened during the period between 3 months and 1 year. Consequently, the ion concentrations remain constant. The fitting equations of the interaction between representative cation concentration and aqueous solution are as follows:

\[
\text{Ca}^{2+}: y = 0.592\exp(1.23/t) \hspace{1cm} (7) \\
\text{K}^+: y = 1.297\exp(0.49/t) \hspace{1cm} (8)
\]

2) Variation law of ion concentration in an aqueous solution on hoary silty mudstone
The variation curves of anion and cation concentrations in an aqueous solution on hoary silty mudstone are shown in Figures 11 and 12, respectively.

A) Cation
The variation curve of cation concentrations in an aqueous solution is similar to the one of light-yellow silty mudstone. Most of those seems to fit exponent well except that of Na$^+$ present fluctuating.
with saturation time because Na\(^+\) in aqueous solution is easily adsorbed on the surface of the rocks that the concentration rends down first. Afterward, the dissoluble mineral in the rocks dissolve, thus increasing the concentration first and then decreasing it again.

B) Anion

It is different among the anion concentrations changing. The concentration of SO\(_4^{2-}\) and NO\(_3^{-}\) decrease remarkably during the first three months. After the third month, the chemical reactions come down to the bottom and get some promotion before the sixth month. Afterward, they level off gradually. The concentration of Cl\(^-\) decreases after the first month and then increases after the third month to a great extent; afterward, it levels off gradually.

The anion changing rule is similar to the process of reaction–diffusion, which is described by Prigogine [18] and can be characterized via dynamic stability analysis. The following equation corresponds to a chemical reaction if \( \frac{dX}{dt} \) is taken for rapidity of reaction and \( \frac{d^2X}{dt^2} \) is taken for acceleration:

\[
A \frac{d^2X}{dt^2} + B \frac{dX}{dt} + Cx = 0.
\]

(9)

A pair of conjugate complex roots exists under certain conditions; two integrals are shown as follows:

\[
y_1(x) = e^{ax} \cos \beta x,
\]

\[
y_2(x) = e^{ax} \sin \beta x
\]

(11)

The general equation is \( y(x) = a e^{ax} \cos \beta x + b e^{ax} \sin \beta x \). According to actual condition, coefficient b is equal to zero. Thus, the general equation of the curve is \( y(t) = a e^{at} \cos \beta t \).

(12)

![Figure 11](image1.png) \hspace{1cm} ![Figure 12](image2.png)

**Figure 11** Variation curve of cation concentrations in an aqueous solution on hoary silty mudstone  
**Figure 12.** Variation curve of anion concentrations in an aqueous solution on hoary silty mudstone

3) Variation law of ion concentration in an aqueous solution on strongly weathered argillaceous siltstone

The variation curves of anion and cation concentrations in an aqueous solution on strongly weathered argillaceous siltstone are shown in Figures 13 and 14, respectively.

A) Cation
The ion concentration curves of Mg$^{2+}$, Al$^{3+}$, Fe$^{3+}$, and Zn$^{2+}$ move minimally that accounting for their compounds is stable. Therefore, hydrolysis and ion exchange can hardly play their role. Nevertheless, the ones of Na$^+$, Ca$^{2+}$, Si$^{4+}$, and K$^+$ move substantially but obtain certain a disciplinarian:

In the first month of water saturation, ion exchange and sorption play a major part on the water–rock interaction, and most ion concentrations in the aqueous solution considerably decrease.

From the first to the third month, the velocities of the reaction gradually slow down and level off in the end.

From the third to the sixth month, almost all reactions gradually achieve their saturation.

After 1 year of water saturation, the curves do not move much. This result is in contrast to that after 6 months. Therefore, water–rock interaction minimally influences the softening of strongly weathered rocks.

B) Anion

The movements of anion concentration are disorderly and ruleless probably due to rock weathering. For example, that of NO$_3^-$ moves up with time, whereas that of SO$_4^{2-}$ drops down to nadir and then stabilizes, thus fitting the exponent perfectly. Meanwhile, that of Cl$^-$ decreases largely before undergoing a slight promotion and then tends to be stable. A certain equation as if damped vibration could fit the curve of Cl$^-$.

Some conclusions are as follows:

(1) The pH value of aqueous solutions decreases gradually while soft rocks are saturated. Thus, a transition from weak alkalescence to acidity occurs.

(2) Three months is a critical time for water–rock reaction. Before this time, chemical exchange and sorption are in full swing; thus, ion concentrations decrease. Nevertheless, the concentrations increase or level off because of the functions wearing off.

(3) The movement of ion concentration curves may follow exponential and dynamic stability (reaction and diffusion). Either way, the dynamic process stabilizes in the end.

(4) The F$^-$, Mn$^{2+}$, Al$^{3+}$, and Fe$^{3+}$ Zn$^{2+}$ ions remain constant during the entire experiment.

![Figure 13. Variation curve of cation concentrations in an aqueous solution on strongly weathered argillaceous siltstone](image)

![Figure 14. Variation curve of anion concentrations in an aqueous solution on strongly weathered argillaceous siltstone](image)

4.5. Variational regularities of mechanical characteristics in the interaction between soft rocks and water

4.5.1. Variational regularities of the compressive strength of soft rocks at different water-saturation periods. Soft rocks in different water-saturation states were subjected to a uniaxial compressive strength test. The results are shown in Table 2.

In reference to the relation formula $R = A \exp(B/t)$, the test values shown in Table 2 were fitted. The results are displayed as follows:

- light-yellow silty mudstone: $R = 0.367 \exp(1.517/t)$,  
- hoary silty mudstone: $R = 0.577 \exp(0.798/t)$.
Table 2. Compressive strength of soft rocks at different water-saturation times (MPa)

| Title of rocks                  | 0     | 1     | 3     | 6      | 12    |
|--------------------------------|-------|-------|-------|--------|-------|
| light-yellow silty mudstone    | 4.510 | 1.682 | 0.594 | 0.921  | 0.423 |
| hoary silty mudstone           | 1.447 | 1.161 | 1.071 | 0.672  | 0.468 |
| strongly weathered argillaceous siltstone | 19.504 | 18.257 | 56.775 | 39.234 | 39.098 |

Figure 15 shows the compressive strength curve of silty mudstone at different water-saturation times. The fitting curve is consistent with the testing curve. The variation of the compressive strength of soft rocks at different water-saturation times is fitted with exponential regularity. The compressive strength of silty mudstone decreases gradually with water-saturation time. During 1–3 months of water saturation, the decreasing range of compressive strength is considerably large. After 3–6 months of water saturation, the decreasing range gradually becomes steady. The point of water-saturation time at which compressive strength is steady is 6 months.

(a)  
(b)

Figure 15. Compressive strength curve of light yellow (a) and hoary (b) silty mudstone at different water saturation times.

4.5.2. Variational regularities of the tensile strength of soft rocks interacting with water. Splitting tensile tests were conducted to obtain the splitting tensile strength of soft rocks at different water-saturation times. The results are shown in Table 3.

Table 3. Tensile strength of different soft rocks at different water-saturation times (MPa).

| Title of rocks                  | 0     | 1     | 3     | 6      | 12    |
|--------------------------------|-------|-------|-------|--------|-------|
| light-yellow silty mudstone    | 0.529 | 0.261 | 0.081 | 0.075  | 0.059 |
| hoary silty mudstone           | 0.430 | 0.204 | 0.092 | 0.073  | 0.0625 |
| strongly weathered argillaceous siltstone | 1.846  | 1.635 | 5.484 | 2.323  | 2.542 |

The formula: $\sigma_t = A \exp(B/t)$ is adopted to fit tensile strength of silty mudstone at different water-saturation times.

Light-yellow silty mudstone:  
$\sigma_t = 0.0525 \exp(1.587/t)$  
(15)
Hoary silty mudstone: \( \sigma_t = 0.0562 \exp(1.277/t) \) \( (16) \)

As shown in Figure 16, the tensile strength of silty mudstone decreases gradually with water-saturation time. The decreasing range of tensile strength is large during 3 months of water saturation. Subsequently, falling range minus and trend to steady after six months.

By contrasting the compressive and tensile strength curves, it is found that variety of compressive strength and compressive strength are simpler.

![Figure 16. Tensile strength curve of light-yellow (a) and hoary (b) silty mudstone at different water saturation times](image)

4.5.3. **Variational regularities of the shear strength of soft rocks interacting with water.** Direct shear test of soft rocks was adopted for the shear strength test. The results are shown in Table 4.

|                     | 0     | 1     | 3     | 6     | 12    |
|---------------------|-------|-------|-------|-------|-------|
|                     | \( C \) \text{(MPa)} | \( \phi (^\circ) \) | \( C \) \text{(MPa)} | \( \phi (^\circ) \) | \( C \) \text{(MPa)} | \( \phi (^\circ) \) |
| light-yellow silty mudstone | 0.61 | 17.8  | 0.80  | 19.0  | 0.39  | 21.4  |
| hoary silty mudstone     | 0.57 | 19.3  | 0.72  | 14.1  | 0.01  | 24.3  | 0.08  | 13.3  |
| strongly weathered argillaceous siltstone | 7.50 | 17.9 | 12.3  | 20.5  | 14.5  | 26.8  | 11.5  | 17.9  | 4.87  | 20.0  |

As a result of the structure and sampling inhomogeneity of soft rocks, the \( C \) and \( \phi \) values of soft rocks at different water-saturation times are irregular. However, the \( C \) and \( \phi \) values change gradually with water-saturation time.

Carbonaceous mudstones are bibulous and expansile, water-saturation time was adjusted to 1 h, 1 day, and 7 days. Direct shear experimentation of the earth was adopted to acquire the shear strength value shown in Table 5.

The \( C \) and \( \phi \) values of carbonaceous mudstone were fitted by the equation \( y = A \exp(B/t) \). The simulation equations of \( C \) and \( \phi \) values and water-saturation time are as follows:

\[
C = 57.666 \exp(0.008/t) \quad (17)
\]

\[
\phi = 18.015 \exp(0.0103/t) \quad (18)
\]
Tab 5. Results of laboratory test on carbonaceous mudstone

| Water saturation time (hour) | 0   | 1   | 24  | 168 |
|----------------------------|-----|-----|-----|-----|
| Water content ω (%)        | 10.42 | 12.71 | 14.80 | 22.40 |
| Volume-weight γ (g/cm³)    | 2.336 | 2.241 | 2.160 | 2.143 |
| C value (KPa)              | 64.2 | 56.8 | 42.3 | 15.2 |
| φ value (°)                | 17.7 | 22.1 | 11.2 | 3.3 |
| Compression modulus E(MPa) | 1.801 | 1.768 | 0.970 | 1.239 |

As shown in Figure 17, the shear strength of carbonaceous mudstone decreases rapidly with water saturation. After 1 h, the c and φ values have hardly changed; After 1 day, the c and φ values have a wider range of drop, that is, the c value decreases by nearly 30%, and the φ value decreases by 40%. After 7 days, shear strength drops dramatically; for example, the c value is only 25% of that of the natural, and the φ value is only as much as 17% of that of the original. Therefore, carbonaceous mudstone softens while interacting water, as evidenced by the rapid and remarkable decrease in strength, thus endangering engineering.

Figure 17. C and φ curves of carbonaceous mudstone at different saturation states

4.6. Relation between variety in structure or composition and mechanical characteristics of soft rocks interacting with water

As an example, the light-yellow silty mudstone has been researched into the relation between variety in structure or composition and mechanical characteristics of soft rocks interacting with water

4.6.1. Relationship between the microstructure and mechanical characteristics of soft rocks. On the basis of the above discussion, the structure of soft rocks is observed via micropolariscopy and SEM. However, identification under the micropolariscope is only cursory method; thus, the fractal dimension Dp value of pore distribution was introduced to study the relation between the structure and mechanical characteristics of soft rocks. Through analysis, the equations reflecting the relationship between the Dp value and compressive strength (R) or tensile strength (σt) can be obtained as follows:

\[ R = 0.367 \exp \left( \frac{1.517}{4.03 + \sqrt[4.03]{588.24D_p} - 1152.59} \right), \]  

\[ \sigma_t = 0.0525 \exp \left( \frac{1.587}{4.03 + \sqrt[4.03]{588.24D_p} - 1152.59} \right). \]  

The relationship curve is shown in Figure 18. With the fractal dimension Dp value of pore distribution increasing, namely, water-saturation time going, soft rocks have been a downtrend of mechanical characteristics and become softer.
Figure 18. Relationship between the fractal dimension of pore distribution and strength of light-yellow silty mudstone

4.6.2. Relationship between the chemical composition and mechanical characteristics of soft rocks. Fe$^{3+}$ is taken for analysis; the simulation equations reflecting the relationship between Fe$^{3+}$ content and the strength of the light-yellow silty mudstone are as follows:

compressive strength: \[ R = 0.01x^2 - 0.0099x + 0.5315, \] (21)
tensile strength: \[ \sigma_t = 0.0006x^2 + 0.0118x + 0.0222. \] (22)

As shown in Figure 19, compressive or tensile strength increases nonlinearly with the increase in Fe$^{3+}$ content because the structure of Fe$^{3+}$ is dense and relatively hard. When the Fe$^{3+}$ content is high, strength also increases. Moreover, the mathematical relationship between Fe$^{3+}$ content and compressive or tensile strength is nonlinear.

Figure 19. Relationship between the Fe$^{3+}$ content of light-yellow silty mudstone and the compressive (a) and tensile (b) strength

4.6.3. Relationship between the chemical composition of the aqueous solution saturating soft rocks and the mechanical characteristics of soft rocks. According to existing research [20], the change of NO$_3^-$ and SO$_4^{2-}$ can reflect the strength change of soft rocks. The representative ion concentration in aqueous solutions, such as NO$_3^-$ and SO$_4^{2-}$, have been investigated. Through calculation and analysis, the relational expressions reflecting the connection between the ion concentration in the aqueous solution and the mechanical strength of light-yellow silty mudstone are followed.

1. Equation of NO$_3^-$ concentration and strength:

compressive strength: \[ R = 0.367 \exp[1.35 \ln(2.26Y_{NO3})], \] (23)
tensile strength: \[ \sigma_t = 0.0525 \exp[1.42 \ln(2.26Y_{NO3})]. \] (24)

The relationship curve is shown in Figure 20. NO$_3^-$ concentration in the aqueous solution decreases gradually with water-saturation time. At one point, the compressive or tensile strength of silty mudstone presents a decreasing trend. The relationship between NO$_3^-$ concentration and compressive
or tensile strength is a direct ratio. Moreover, the compressive or tensile strength varies within the same range.

![Figure 20. Relationship between NO$_3^-$ ion concentration and the compressive (a) and tensile (b) strength in light-yellow silty mudstone aqueous solution](image)

Figure 20. Relationship between NO$_3^-$ ion concentration and the compressive (a) and tensile (b) strength in light-yellow silty mudstone aqueous solution

2. Equation of SO$_4^{2-}$ concentration and strength:

compressive strength: 
$$R = 0.367 \exp \left[ 1.548 \ln \left( \frac{0.286 \times Y_{SO4^2-}}{T} \right) \right]$$

(25)

tensile strength: 
$$\sigma_t = 0.0525 \exp \left[ 1.62 \ln \left( \frac{0.286 \times Y_{SO4^2-}}{T} \right) \right]$$

(26)

As shown in Figure 21, strength changes by SO$_4^{2-}$ or NO$_3^-$ concentration vary. SO$_4^{2-}$ concentration decreases gradually with time. In the meantime, compressive or tensile strength decreases at a wide range.

![Figure 21. Relationship between SO$_4^{2-}$ ion concentration and compressive (a) and tensile (b) strength in shallow yellow silty mudstone aqueous solution](image)

Figure 21. Relationship between SO$_4^{2-}$ ion concentration and compressive (a) and tensile (b) strength in shallow yellow silty mudstone aqueous solution

5. Softening mechanisms of the mechanical properties of soft rocks interacting with water

5.1. Expanding and crumbling of sialite water-absorbed mechanism

Soft rocks in engineering environments usually contain sialite. When interacting with water, they expand and crumble. Sialite grains, such as kaolinite and illite, which have strong water affinity, are smaller. While interacting with water, water molecules come into sialite grains showing layer conditions and form polarizable layers of water molecules. Then, the molecules reabsorb water to expand the layers. Meanwhile, water molecules come into layers of unit cells of sialite to form water layers inside minerals. As to the water molecule, coming into spacing among grains is easier than that among layers of gains. The former leads to the external expansion of sialite, whereas the latter results in internal expansion. Research has shown that the physical and chemical reactions between illite and
water result in the expansion of soft rocks. It increases the original volume by 50%–60% of the original. The following chemical reaction equation is followed:

\[ K_{0.9}Al_{2.9}Si_{3.1}O_{10}(OH)_{2} + nH_{2}O \rightarrow K_{0.9}Si_{2.9}O_{10} \cdot (OH) \cdot H_{2}O. \]  

(27)

After saturation, sialite in soft rocks can absorb substantial moisture. As a result, the spaces between unit cells become increscent, or pervasion layers become thick, and clay binders crumble. Grains of crumb lose connections to disaggregate gravity. As a result of the asymmetric expansion of sialite, the inside of soft rocks produces asymmetric stress, enabling abundant tiny holes to destroy the internal structural system of crude rocks and grains of rocks to smash and disaggregate [21]. Apparently, the expansion and disintegration of soft rocks result from the content or style of sialite, the type of clay binder, and the degree of concretion. High-expansion sialite has higher content, and its characteristics of expansion and disintegration are clearer. Soft rocks contain argillaceous cement that has stronger expansion and disintegration compared with rocks containing calcareous or siliceous cement.

Research on sialite of soft rocks has mostly focused on kaolinite and illite, which exhibit short expansion. However, anisotropism of free swell ratio is more evident. For example, the vertical bedding direction of the free swell ratio of light-yellow silty mudstone and parallel bedding is 0.562% and 0.197%, respectively. This kind of soft rock has strong expansion; thus, breakup shapes of bit along the bedding and vertical joint direction.

5.2. Mechanism of ionic exchange and absorption

The results of hydrochemical analysis are as follows: During the first stage, water–rock chemical interaction mostly shows the process of ionic exchange and absorption. However, the ion exchange from minerals cannot proliferate rapidly in the water solution; thus, ion concentration has a wide decreasing range. Research [3, 5] has shown that while under a nonhydrostatic state of stress, liquid membranes exist among grains of solid. Liquid membranes have a thin ply and strong surface action that are enough to transfer direct and support leaning stress. During the initial stage of water–rock interaction, ion exchange in the water solution probably occurs in the membrane above, resulting in a wide decreasing range of ion concentration in the water solution. With the development of ion exchange and adsorption, the ion concentration in the membrane increases, thus releasing ions. Moreover, results of mechanical tests reflect that mechanical strength has the largest extent of decline during the first stage of water–rock chemical interaction. Therefore, the action of ionic exchange and absorption is believed to be one of the reasons why soft rocks further soften when interacting with water.

The process of ionic exchange and absorption action resulting in the decline of mechanical characteristics is shown in Figure 22, followed by the analysis of the mechanism.

![Figure 22. Analysis chart of ionic exchange and absorption](image)

First, ion exchange absorbs energy in three ways:

1. **Diadochy.** It is a general matter for the diadochy of silicon-oxy tetrahedron wafer Al³⁺, Si⁴⁺, Mg²⁺, and Al³⁺. The action causes a negative electric charge shipment on the cleavage surface, followed by the absorption of cations.
(2) Bond rupture. This phenomenon often exists on the surface of the clay grains’ edge or the noncleavage surface. The operation intensifies as the clay grains are reduced. Negative electronics with one side of bond rupture while positive on the other side. Both powers the exchange.

(3) Hydrogen exchange of exposure hydorcarbyl. The exposure of hydorcarbyl on the surface and edge of clay grains leads to the breakdown of it. Meanwhile, the clay grains are greatly affected by the pH value, and the possibility of the entrance of H\(^+\) into the solution increases while the value increases with the effective negative electronics of the grains have more.

Second, the reaction process of the ion exchange absorption between water and rocks is affected by several factors, such as the mineral composition and structure density of soft rocks and the chemicals, concentration, and pH value of the solution. The total quantity of positive ion electronics absorbed by the clay remains under a situation of nonenergy exchange or few energy exchange. The ion exchange between water and clay mineral grains reaches equilibrium while most exchanges and absorption work in the situation. The balance breaks when the chemicals of the environment water changes, that is, the ions diffuse quickly with the exchange and absorption of ions. Furthermore, the structure of soft rocks changes.

Lastly, the mineral composition of clay controls the size, shape, and surface characteristics of grains and thus can define the plastic, expansion, condense, and strength of soft rocks and the conductivity of water alone or by the interaction with liquid. The exchange capability of clay minerals is not fixed but depends on compositional and environment factors. The change of environmental water chemicals leads to the production of additional negative electronics of clay minerals via diadochy, thus providing strong surface characteristics to clay grains. The physical mechanical characteristics and chemical-physical characteristics of clay affected by the gravitation and repulsion changes between grains which is the result of bi-layer changes caused by surplus negative electronics balanced by K\(^+\), Na\(^+\), and Ca\(^{2+}\).

### 5.3. Dissolution of soluble minerals and creation of minerals

A layer of membrane exists between water and rocks; this membrane can absorb reaction molecules and ions in the water solution, thereby keeping the reaction molecules and ion concentration in the membrane higher than the outer environment. The absorption action is called surface absorption, which can be classified into two types, i.e., physical and chemical. Physical absorption is caused by the power between molecules (i.e., Van Dehua power) with no new chemical bonds which had small changes in absorbing molecules structure. The speed of physical absorption is fast, with low active and absorbing heat energy at 8.368–25.10 KJ/mol. Chemical bonds often occur in the chemical absorbing action, which has surface activate complex. Chemical absorption needs active energy while absorbing heat energy and is high at 83.72 KJ/mol [23]. The active energy of chemical action which exist surface absorbing should be

\[
E_a = E - Q_A \tag{28}
\]

E denotes real activated energy. \(E_a\) is the present action activate energy, and \(Q_A\) is the absorbing heat. Catalyze gets through the activate energy reduces by surface absorbing especially chemical from Equation (28). Soft rocks contain rich clay grains with a large specific surface area and surface energy, which is the relative active part. The preconditions for the dissolution of soluble minerals in soft rocks dissolve under natural conditions are activate action and strong surface energy.

The chemical analysis result of this solution shows that the solution ionic concentration after the interaction of soft rocks and water is not as high as expected. The reason for this question goes to the bondage of most part of ions by membrane between soft rocks and water, and also goes to the relative small quantity of mineral dissolved in. In summary, the process of this reaction between soft rocks and water is complicated; thus, its mechanism requires further research.

The experiment shows the changes of active ions in solutions, such as Na\(^+\), Ca\(^{2+}\), K\(^+\), Cl\(^-\), and SO\(_4^{2-}\) considerably fluctuates. Thus, there is a consultation that mineral corrosion action and a secondary creating action occurs in the process of soft rock–water interaction. The possible chemical action is as follows:
\[
KAl_3Si_2O_10(OH)_2 + 6SiO_2 + 2K^+ = 3KAlSi_3O_8 + 2H^+ \quad (29)
\]
(Muscovite crystal transfer to microcline crystal)

\[
KAl_3Si_2O_10(OH)_2 + 6SiO_2 + 3Na^+ = 3NaAlSi_3O_8 + 2H^+ + K^+ \quad (30)
\]
(Muscovite crystal transfer to albite crystal)

\[
2KAl_3Si_2O_8 + 2H^+ + 9H_2O \leftrightarrow Al_2Si_2O_5(OH)_4 + 2K^+ + 4H_4SiO_4 \quad (31)
\]
(Dissolution of potash feldspar and formation of kaolinite)

\[
2NaAlSi_2O_8 + 2H^+ + 9H_2O \leftrightarrow Al_2Si_2O_5(OH)_4 + 2Na^+ + 4H_4SiO_4 \quad (32)
\]
(Formation of kaolinite by albite, water, and ion exchange)

The outcome of H\(^+\) in the action list above reduces the pH value of the solution. The formation of microacid environments is avail of the formation of kaolinite. The mineral X-ray diffraction files show the formation of kaolinite. Though the peak value of diffraction, all depends on the diffraction angle. The two characteristics of kaolinite increases as water saturation is prolonged. This phenomenon is highly related to the secondary creation of kaolinite minerals in soft rocks.

| Name of rocks                     | dvalue(Å) | Natural state | Water saturation (1 month) | Water saturation (3 months) | Water saturation (6 months) | Water saturation (1 year) |
|----------------------------------|-----------|---------------|-----------------------------|----------------------------|----------------------------|----------------------------|
| Light-yellow silty mudstone      | 7.13      | 9             | 11                          | 15                         | 17                         | 14                         |
| Hoary silty mudstone             | 3.57      | 6             | 9                           | 12                         | 10                         | 9                          |
| Hoary silty mudstone             | 7.13      | 9             | 15                          | 16                         | 11                         | 11                         |
| Hoary silty mudstone             | 3.57      | 7             | 12                          | 16                         | 9                          | 8                          |

**Table 6. Diffraction intensity peak value at different saturated states of kaolinite**

5.4. Micromechanical mechanism of soft rock–water reaction

Raj and Ashby (1971) established a theoretical model for rock distortion under the action of low stress, which occurs during grain edge movement, including expansion matter movement. While rocks are destroyed under the action of stress, the edges of grains A and B mismoves. The zigzag and irregular edges that contact with each other become smooth when the solution penetrates the spaces and perform chemical action with rock grains, resulting in rockinner cohesion and decrease in internal friction. Consequently, the mechanic strength of rock is reduced. It is the theory that promote the softening of the mechanical characteristics of soft rocks during the dissolution of minerals and the creation of water–rock chemical reaction.

5.5. Nonlinear chemical and dynamic mechanism of soft rock softening

From the perspective of solution ion concentration, soft rock softening is a nonlinear dynamic process. Every space location in the chemical system structured by soft rock and solution has an expansion trend caused by concentration space grads when the system component concentration is distributed irregularly. Every part contained in the system is affected by series of chemical reactions, which exist in the system’s contemporary and expansion course. Give \( \mathbf{\varphi} \) to the reaction speed number \( p \), \( \mathbf{\varphi} \) for the stoichiometric index of part number \( i \). The reaction speed and expansion trend are defined by mole fraction \( X_i \). The equation is obtained as follows:

\[
\frac{\partial X_i}{\partial t} = f_i \left( \{ x_j \}, \mathbf{\lambda} \right) - \nabla \cdot \mathbf{\varphi}_i, \quad (1, j=1,2, \ldots),
\]  

(33)
where \( f_i \) is the total change speed of concentration of part number \( i \) (\( X_i \)) in the unit volume caused or consumed by chemical reaction, and \( f_i \) is decided by the system’s dynamic conditions. All the terms presented by a control parameter \( \lambda \) there in before. The value of \( \lambda \) reflects the degree of system control and departure from thermodynamics. \( f_i \) presents the effect of chemical reaction.

Under the assumption that the expansion course satisfies the Fick expansion law and neglects the coupling of the parts’ expansion trends, the part concentration change speed caused by the expansion course can be presented by

\[
\frac{\partial X_i}{\partial t}_{\text{expansion}} = D_i \nabla^2 X_i, \quad (34)
\]

\[
\frac{\partial X_i}{\partial t} = f_i((X_i), \lambda) + D_i \nabla^2 X_i. \quad (35)
\]

The equation can be solved when the first (concentration of the parts on the boundary surface is kept unchanged), second (trends are kept unchanged), and third boundary conditions (periodic boundary condition) are satisfied. In accordance with the definition of stability and Lyapounov stability theory, stability can be treated through this linear stability. The answer can be presented through differential equation groups.

\[
\frac{dX}{dt} = f_1(X, Y),
\]

\[
\frac{dY}{dt} = f_2(X, Y), \quad (36)
\]

where \( \frac{dX}{dt} \) is the speed of chemical reaction, and \( \frac{dY}{dt} \) is the acceleration of chemical reaction.

If the system is subject to a small disturbance, then the behavior of the system can be obtained by the linear stability analysis of Equation (36).

\[
\begin{align*}
X(t) &= X_s + x(t) \\
Y(t) &= Y_s + y(t)
\end{align*}
\]

Equation (37) is substituted into (36), and the stationary state \((X_s, Y_s)\) is taken as the reference state. The nonlinear items are neglected.

\[
\begin{align*}
\frac{dx}{dt} &= a_{11}x + a_{12}y \\
\frac{dy}{dt} &= a_{21}x + a_{22}y
\end{align*} \quad (38)
\]

The general style of the solution is

\[
\begin{align*}
x &= C_1A_1e^{\omega_1t} + C_2A_2e^{\omega_2t} \\
y &= C_1B_1e^{\omega_1t} + C_2B_2e^{\omega_2t}
\end{align*} \quad (39)
\]

For example, the dynamic rules shown by the dynamic change curve (Figures 11 and 12) of the positive and negative ions in the solution after hoary silty mudstone encountering water fulfilled the equation characteristics. The equation group has two special solutions that is the ion concentration change curve studied in the subject. Overall, the chemical reaction mechanism of water–rock reaction is a nonlinear process.

6 Application of study results on the analysis of BIII2 slope stability

6.1. Selection of calculative parameters

The BIII2 slope lies to the section marked pile number 13+785–13+885 in the WSRPDS. The light-black carbonaceous mudstone indicates weathering in the construction; the thickness is 3–5 m. The
initial stages of carbonaceous mudstone excavation have definite strength and bearing capacity. However, the excavation immediately becomes muddy after waterlogging. The slope produces a few sliding motions due to rain and negatively influences the construction course. According to expeditionary research on the spot, the radical reason for this phenomenon is that the expansion soil at the top of the slope and the entire weathered mudstone had been expanding or softening while interacting with water.

The Shear strength of the slide area is an important parameter for the stability calculation and the consolidation design of landslips [27]. As a result of keeping in the groundwater, BIII2 slip masses, such as rock or soil, interact with water. At the external of BIII2 slope, versicolor eluvial soil containing abundant sialite expands when it interacts with water. By contrast, carbonaceous mudstone at the feet becomes speedily silty. The land slip area made up of rock and soil has great variability. Thus, the following methods are introduced to select the synthetic parameters of shear strength:

1. To simulate an actual mechanical environment of slope and acquire an index of peak value or residual strength, laboratory saturation tests are conducted on the rock and soil of the slide area.

2. In accordance with local specifications and experience of experts, empirical shear strength is provided.

As shown in Table 7, physicomechanical parameters are chosen by summing up the methods described above and through the synthetic analysis of geological conditions, origins, or affecting factors.

| Title                  | Natural unit weight (kN/m³) | Moisture content (%) | Natural state | Saturated unit weight (KN/m³) | Water saturation state |
|------------------------|----------------------------|----------------------|---------------|-------------------------------|-----------------------|
| Eluvial soil           | 19.6                       | 28                   | 12 10         | 1.604                         | 20.2 10 8 1.241       |
| Black carbonaceous mudstone | 21.0                      | 13                   | 10 8          | 1.801                         | 22.0 8 7 0.97         |

6.2. Results of the stability calculation of the BIII2 slope

The BIII2 slope has three cross sections. The 6-6 cross section is selected for calculation in the stability analysis of the slope because of the main control section.

In accordance with the finite element method, Marc software of nonlinear finite element is adopted to analyze the stability of the 6-6 cross section. During the calculation, cross sections are treated by the strain of plane. The boundary conditions are horizontal constraints of the left or right, and X, Y restrict of lower.

As shown in Figure 23, the plastic zone of the 6-6 cross section passes through the feet to the top of the slope. Most parts of the plastic strain zone are concentrated on one position to form the slide zone. Stability coefficient is calculated such as 0.83, by corresponding slide plane of 6−6 cross section in the preceding of plastic strain zone run-through, indicating that the BIII2 slope has been unstable.
7. Conclusions

(1) Interaction between soft rocks and water includes physical, chemical, and mechanical action; Chemical and micro- mechanical action should be leading for the soft rocks contained plentiful sialite.

(2) After soft rocks interact with water, physical characteristics, such as moisture content or unit weight, have definite regularity. The moisture capacity extent has a wide range from the first to the third month and develops an easy curve over three months before settling down to a stable value C. As a result of different bound-water-course thicknesses, the increasing range of the moisture capacity of soft rocks vary from each other. However, the unit weight of soft rocks decreases with time.

(3) Results of the research on the microstructure of soft rocks are as follows: Porosity is aggravated with water-saturation time, and the connections among grains loosen. The structures appear to have transformed from relatively compact and high-intensive stripped or granular structures into loosened and porous clover-leaf ones. The fractal dimension $D_p$ of pore distribution increases remarkably from 6–12 months of water saturation. After 6 months, the microstructures loosen up; thus, the mechanical characteristics of soft rocks considerably decline.

(4) After soft rocks interact with water, the mechanical characteristics of rock decline with water-saturation time. Research on the regularities inducing this phenomenon are conducted by the mineral composition, chemical composition, and microstructure of soft rocks and the pH value of the aqueous solution. A series of dynamic evolvement processes that occur on the microstructure of soft rocks result in the decline of mechanical characteristics.

The following conclusions can be drawn:

(a) Soft rocks demonstrate qualitative change in 3 months, regardless of composition, microstructure, or mechanical characteristics.

(b) At the natural station of soft rocks, strength is lower so that softened extent is higher.

(5) Whether chemical composition of solution or compressive (tensile or shear) strength, soft rocks saturated meet the following quantitative relations:

(a) exponential curve

(b) kinetic stability equation (reaction–pervasion equation)

(6) The softening micromechanisms of saturated soft rocks are as follows: expanding and crumbling mechanism, ionic exchange and absorption mechanism, dissolution of soluble minerals and creation of
a secondary mineral mechanism, micromechanical mechanism, and nonlinear dynamic mechanism. Synthetic actions result in the decline of the mechanical characteristics and the softening of soft rocks.

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