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Stability Evaluation of Bio-treated Slope under Rainfall Conditions Based on Numerical Simulation

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ABSTRACT

Rainfall infiltration is the main trigger of slope failure. Currently, the approach known as biomineralization technology has been widely studied for the purpose of rainfall erosion resistance. However, the research on the effectiveness of reinforcement by biomineralization technology on slope stability is extremely limited. In this study, the finite element method (FEM) was used to simulate the rainfall infiltration in the slope and study the effect of biotreatment on the rainwater infiltration process. The numerical simulation results show that rainwater infiltration will lead to the reduction of slope stability. The increase of pore water pressure caused by rainwater infiltration will reduce the shear strength of soil. Due to the decrease of permeability after biotreatment, the surface biotreatment measures can effectively reduce the rainwater infiltration. Compared with original slope, the stability of slope reinforced by surface treatment and bio-pile is significantly enhanced. This research lays a solid foundation for the application of slope reinforcement by biomineralization technology.

Keywords: Biomineralization technology, Slope stability, Numerical simulation, rainfall infiltration

1 INTRODUCTION

Abundant rainfall often leads to the unsaturated state of the soil of the slope. Continuous rainfall makes the rainwater infiltrate into the soil of the slope, resulting in the increase of water saturation of soil of the slope and the decrease of the matric suction of the unsaturated soil. As a result, the shear strength of soil of the slope is greatly reduced, and the possibility of landslide is greatly increased. Moreover, the increase of pore water pressure in soil caused by rainfall is an important cause of slope instability (Shi et al., 2016). The natural disaster of landslide poses a serious threat to the normal operation of surrounding infrastructure such as bridges, pipelines, railway and highways as well as the personal safety of nearby residents (Bian & Li, 2018; Li et al., 2017; Cui et al., 2007).

Conventional slope reinforcement techniques include the use of geogrid, steel mesh, soil nails, shotcrete, and ground anchors, etc (Yu & Tan, 2012; Hao et al., 2014; Cao et al., 2011; Xiao, 2021). Additionally, geogrid, steel mesh, and soil nails are appropriate when the slope surface needs to be kept level and appealing; shotcrete reinforcement is appropriate when the entire slope needs to be stabilized; and ground anchor reinforcement is appropriate when the entire slope needs to be stabilized. A geogrid is a grid-like structure that can be used to stabilize soil and is comprised of high-strength polyester or fiberglass strands. The geogrid has been widely utilized in slope reinforcement because of its advantages of light weight, simple construction, and low cost. Steel bars and wire mesh are woven together to form steel mesh sheets, which are thin sheets that can be used to support concrete or soil. Because of the high strength and resistance to corrosion, it is ideal for components that need greater strength, such as the incline of a roadway. High-strength concrete known as shotcrete reinforcement can be sprayed on the surface of a slope or down deep into the ground to create a strong barrier. Slope reinforcement has made extensive use of it because to its benefits of high strength and outstanding durability. To strengthen the stability of the slope, soil nailing entails drilling holes on the slope's surface or deep under the soil, then securing steel bars or steel mesh sheets in the holes to create a nailing system. It has been widely utilized in slope reinforcement because of its easy fabrication and strong durability. In order to strengthen the stability of the slope, ground anchor reinforcement entails fixing

steel anchor rods in the rock formation within the slope or deeply into the soil. It is suitable for enhancing the slope's overall stability and provides the benefits of firmness and longevity.
Although traditional reinforcement technology can obtain better reinforcement effects, there are also problems such as high construction costs, complex construction technology, high maintenance costs, and difficult maintenance renewal. Biomedical technology is a green method that uses microorganisms to biochemical reactions to soil, concrete and other materials to solidify it, thereby improving the mechanical properties of geomorphological materials. Biomineralization technology has a wide range of applications, including soil stabilization, concrete repair, dust control, waste management and other fields (Kumari et al., 2014; Hamdan & Kavazanjian, 2016; Zhan et al., 2016; Duo et al., 2018; Khushnood et al., 2020; Sun et al., 2022). Biomineralization technology has the advantages of small construction disturbance, low price, simple process, etc., so the research of multi-purpose and multi-application scenarios has been carried out. When biomineralization technology is used for soil solidification, the shear strength of soil can be improved， and the permeability of soil can be reduced. At present, some scholars have carried out experiments on the application of biomineralization technology in slope treatment, and pointed out that biomineralization technology can improve the slope resistance to wind erosion, rain erosion and stability. However, the numerical simulation of slope stability after biomineralization treatment is relatively limited. In this study, numerical simulation with finite element method (FEM) was applied to investigate the stability of untreated and biotreated slope under rainfall conditions. The effects of rainwater infiltration on the pore water pressure and stability of slope were discussed.

2 ESTABLISHMENT OF NUMERICAL MODEL

2.1 Geometric dimensions of the model

The software used in this study is MIDAS GTS. The slope model in this study is three-dimensional homogeneous slope, and the specific size is shown in Fig. 1. In order to reduce the effect of boundary on simulation results, geometric model of a slope with the length of 120 m, the height of 60 m, the width of 20 m and the gradient of 0.75 was designed. The Mohr-Coulomb constitutive model was adopted and the soil was assumed as an ideal elastic-plastic material.

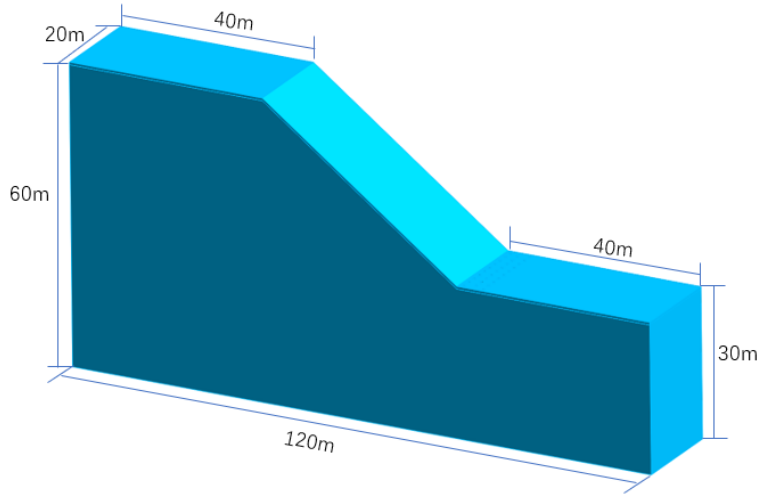
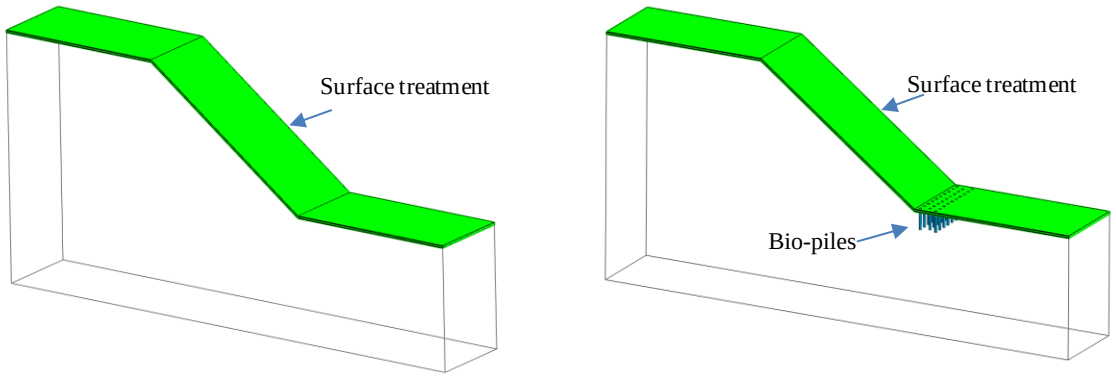


Figure 1. *The geometric dimensions of the model*

2.2 Reinforcement plan

In this study, two reinforcement plans were applied. In the first reinforcement plan, we adopted biomineralization technology to do the surface bio-treatment with a treatment depth of 0.5 m, as shown in Fig. 2(a). By contrast, biomineralization technology were utilized to do the surface bio-treatment and make bio-piles at the toe of slope in the second reinforcement plan, as shown in Fig. 2(b). The pile diameter and pile length are 0.6 m and 5 m, respectively. The pile distance is set to 2 m. Three rows of piles were placed at the toe of the slope. At the same time, original slope without any reinforcement measures was selected as control group to estimate the reinforcement effect of other two reinforcement plan.



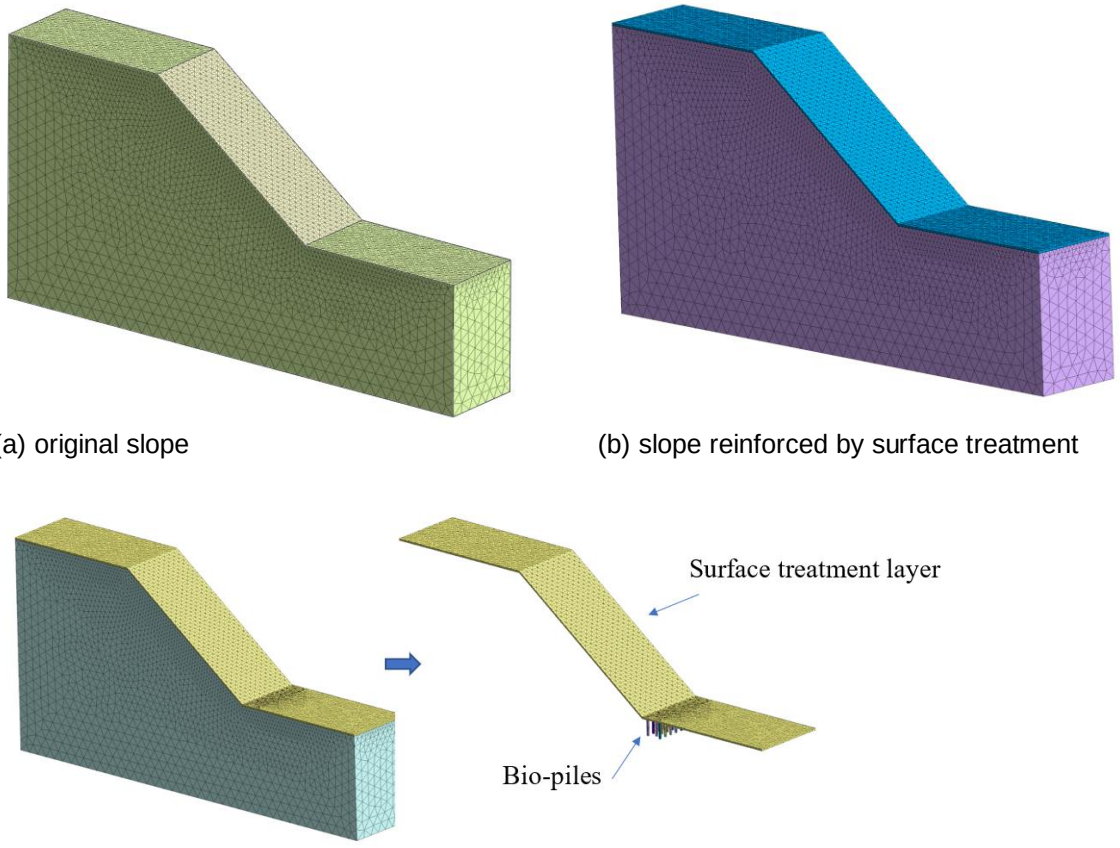
(a) surface treatment

(b) surface treatment and reinforcement of bio-piles at the toe of slope

Figure 2. *Reinforcement plans*

2.3 Mesh generation

Three numerical simulation models were established in this study. The mesh generation of these three models were shown in Fig. 3. Specifically, the first one is the original slope model, as shown in Fig. 3(a). Another one is the surface reinforced slope with a biotreatment depth of 0.5 m, as shown in Fig. 3(b). The third one is the slope reinforced by surface treatment and bio-piles, as shown in Fig. 3(c). In order to improve the accuracy of simulation, the meshing of model slope is dense, which makes it more sensitive in the process of iterative calculation. The mesh size of the part close to the slope surface was controlled at about 1 m, while the mesh size away from the slope surface was controlled at about 3 m.



(a) original slope

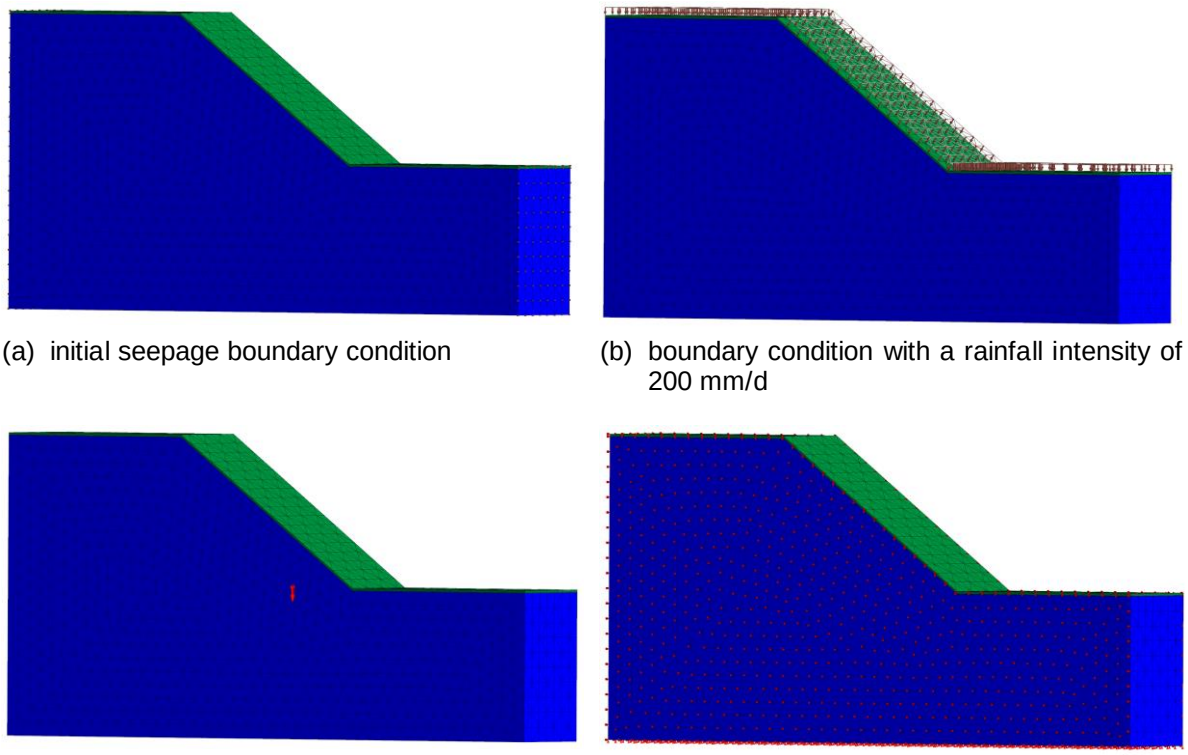
(b) slope reinforced by surface treatment

(c) slope reinforced by surface treatment and bio-piles

Figure 3. *Mesh generation of different models*

2.4 Boundary condition and load application

The boundary condition and load application were shown in Fig. 4. The initial seepage boundary conditions are as follows: the height of left water head and the height of right head are 30 m and 20 m, respectively. The water head difference is 10m. The initial seepage boundary condition is shown in Fig. 4(a). The rainfall intensity was considered as long-lasting heavy rainstorm, with a rainfall of 200mm/d and a duration of 10 hours. The rainfall boundary condition is shown in Fig. 4(b). The load application only considers self-weight, as shown in Fig. 4(c). Static boundary conditions were set for non-slope positions, as shown in Fig. 4(d). The lateral displacement of the model was constrained and the displacement at the bottom of the model was fixed.



(a) initial seepage boundary condition

(b) boundary condition with a rainfall intensity of 200 mm/d

(c) self-weight loading

(d) static boundary condition

Figure 4. *Boundary conditions and load application of model*

2.5 Parameters of model

Some parameters for the simulation model in this study were derived from the literature (Liu, 2021). The model parameters are composed of soil-water characteristic curve, physical and mechanical parameters, as shown in Table 1. The strength parameter of the soil of the slope was obtained from the solidification test, while the soil-water characteristic curve parameter was replaced by the VG model fitting value.

Table 1. *Geomechanics parameters of model*

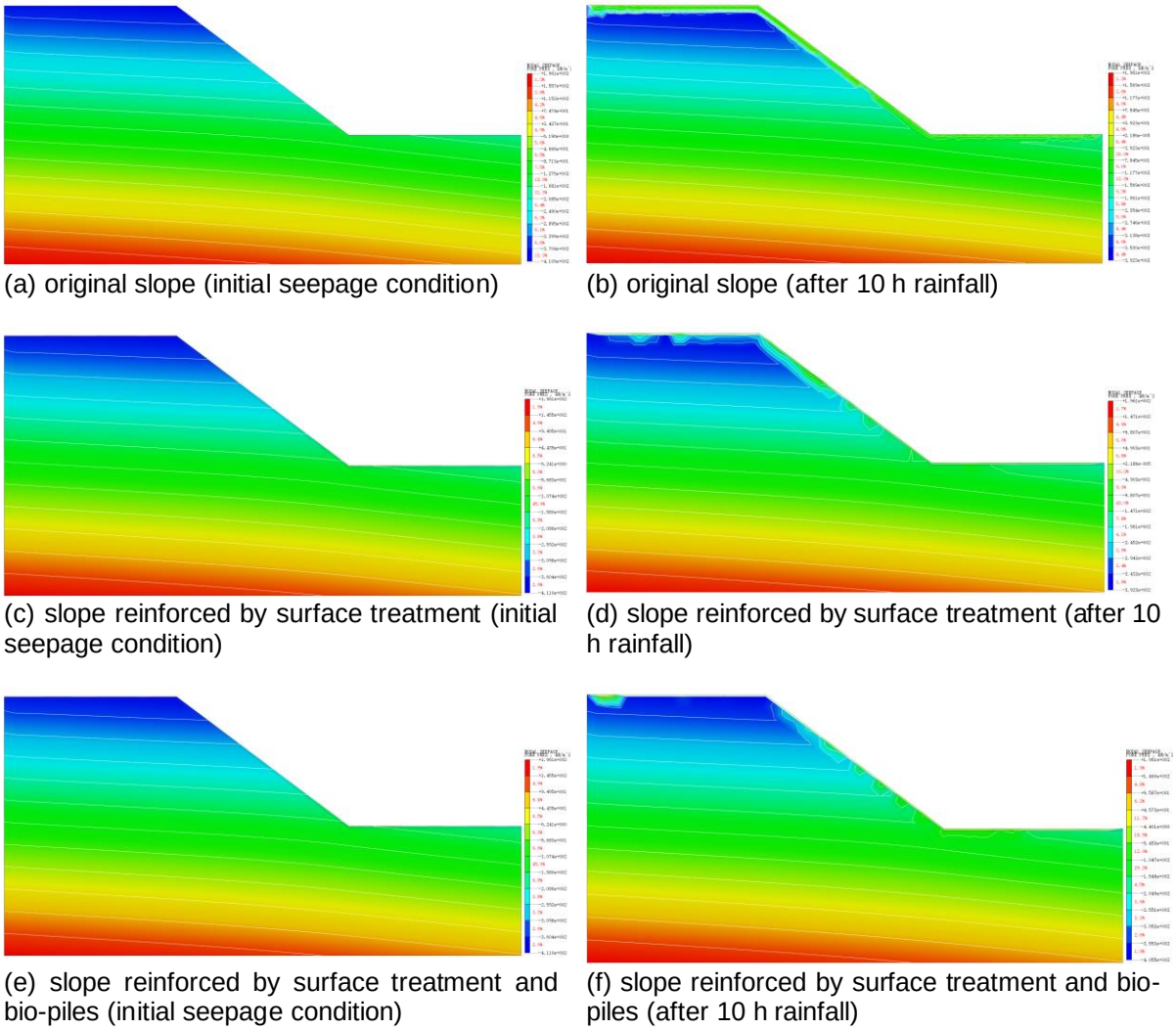
parameters	Original soil	Bio-treated soil
Unit weight / (kN·m^{-3})	19.7	21.4
Cohesive force / (kPa)	2	10
Internal friction angle / (°)	25	32
Elasticity modulus (MPa)	8	13
Poissons ratio	0.25	0.2
Residual water content θ_r	0.197	0.054
Saturated water content θ_s	0.517	0.308
Shape parameter m	0.065	0.213
Pore distribution index n	1.07	1.27

Calibration parameter a	0.006	0.031

3 RESULTS AND DISCUSSION

3.1 Pore water pressure

Fig. 4(a, b, c) are the cloud picture of pore water pressure of the original slope and the reinforced slopes with two different reinforcement plans under the initial seepage boundary condition. It can be seen that under the initial seepage boundary, the bio-treated measure will not have a significant impact on the seepage field and pore water pressure distribution inside the slope. Fig. 4(b), Fig. 4(d) and Fig. 4(f) are the cloud pictures of pore water pressure of the original and reinforced slope after 10 h rainfall. It can be seen that under the influence of continuous rainfall, rainwater will continue to infiltrate into the interior of the slope. The pore water pressure at the slope top, slope surface and slope foot continues to rise. In addition, it can be seen that despite the surface biotreatment, under the influence of continuous rainfall, rainwater will continue to infiltrate into the interior of the slope. At the same time, compared with the untreated slope, it can be clearly found that under the same rainfall duration, the increase in pore water pressure at the slope top, slope surface and slope foot of the biotreated slope is less than that of the untreated slope. The reason is that after bio-treatment, the permeability of the surface soil decreases, hindering the infiltration of rainwater, resulting in a small increase in pore water pressure.



(a) original slope (initial seepage condition)

(b) original slope (after 10 h rainfall)

(c) slope reinforced by surface treatment (initial seepage condition)

(d) slope reinforced by surface treatment (after 10 h rainfall)

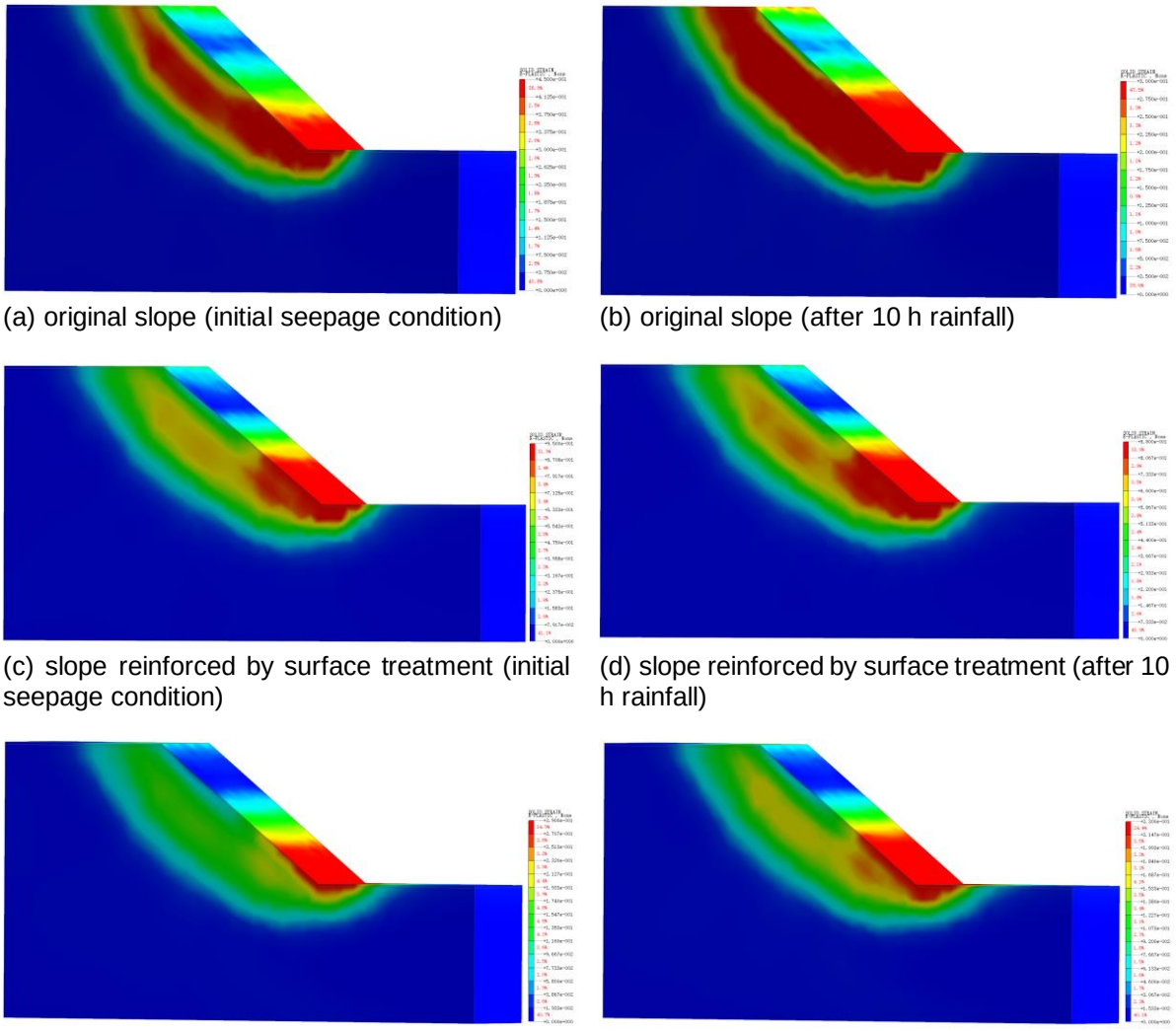
(e) slope reinforced by surface treatment and bio-piles (initial seepage condition)

(f) slope reinforced by surface treatment and bio-piles (after 10 h rainfall)

Figure 5. *Cloud pictures of pore water pressure of untreated and bio-treated slope under rainfall condition*

3.2 Potential slip surface

As can be seen from Fig. 6(a), under the influence of initial seepage field, the potential slip surface of the untreated slope runs through the top and foot of the slope, and the overall stability of the slope is poor. After 10 hours of rainfall, the potential slip surface developed inward towards the slope, and the potential slip area expanded, as shown in Fig. 6(b). The reason for this phenomenon is that rainfall infiltration increases the water content inside the slope. The increase of water content will lead to the increase of pore water pressure and the decrease of shear strength of soil, which will affect the stability of slope. The potential slip surface of the biotreated slope is shallow and doesn't run from the toe to the top of the slope, as shown in Fig. 6(c). The reason is that the surface treatment of the slope has a restraining effect on the slope deformation and sliding, thus enhancing the stability of the slope. As can be seen in Fig. 6(d), after 10 hours of rainfall, the potential slip surface further developed from the toe of the slope to the top of the slope, but it still did not reach the top. The stability of the slope was affected by the rainfall. However, compared with the untreated slope, the effect of biotreated measures for slope stability enhancement is obvious. Meanwhile, when combining the surface treatment and bio-piles to reinforce the slope, it is clearly to find that maximum plastic zone become shallow and mainly distribute near the toe of slope, as shown in Fig. 6(e). Even after 10 h rainfall, the plastic zone of slope reinforced by combined measures didn't expand a lot, as shown in Fig. 6(f).



(a) original slope (initial seepage condition)

(b) original slope (after 10 h rainfall)

(c) slope reinforced by surface treatment (initial seepage condition)

(d) slope reinforced by surface treatment (after 10 h rainfall)

(e) slope reinforced by surface treatment and bio-piles (initial seepage condition)

(f) slope reinforced by surface treatment and bio-piles (after 10 h rainfall)

Figure 6. *Potential slip surface of untreated and bio-treated slope under different conditions*

3.3 Safety factor

Fig. 7 shows the change law of safety factor of slope with different reinforcement measures before and after rainfall. As shown in Fig. 7, the safety factors of both original slope and reinforced slope shows a downward trend as the rainfall continues. That is to say, the rainwater infiltration has a remarkable effect on the stability of both untreated slope and reinforced slope. In addition, the reinforced slopes have higher initial safety factor than original slope because of the reinforcement measures of surface treatment and bio-piles. What's more, the safety factors of slope reinforced by surface treatment and bio-piles are bigger than the slope only reinforced by surface treatment whether it rains or not. The main reasons include two aspects. One is the surface treatment measure decreases the permeability of soil and impedes the infiltration of rainfall. On the other hand, the bio-piles made by biomineralization technology restrain the deep displacement of the slope.

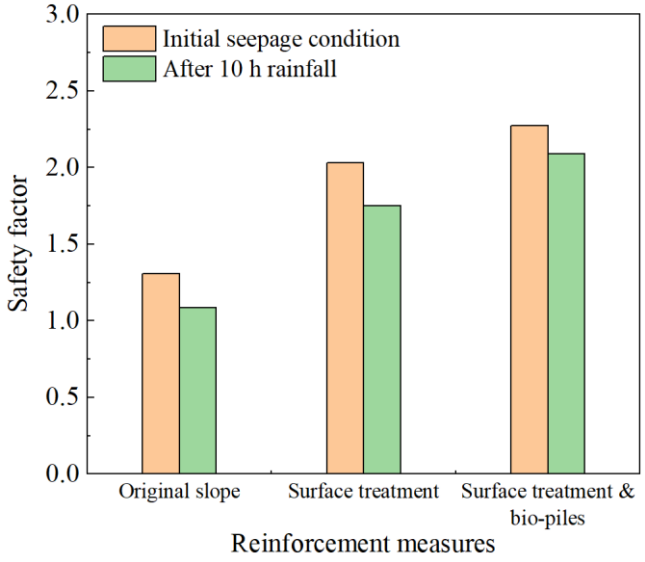


Figure 7. *Safety factor of slope with different reinforcement measures before and after rainfall*

4 CONCLUSIONS

In this study, the stability of slopes reinforced by different reinforcement measures under rainfall condition was investigated using numerical simulation with the finite element method (FEM). The effects of rainwater infiltration on the pore water pressure and stability of slope were analysed. The major findings are as follows:

(1) Under the influence of continuous rainfall, rainwater will continue to infiltrate into the interior of the slope. Compared with the original slope, it can be clearly found that the increase of pore water pressure in the reinforced slope is less than the untreated slope under the same rainfall duration.

(2) Reinforcement measures including surface treatment and bio-pile have a restraining effect on the slope deformation and sliding, thus enhancing the stability of the slope.

(3) Whether the slope is reinforced or not, the safety factors decrease under rainfall condition. However, compared with the original slope, the safety factors of reinforced slope are higher than the unreinforced slope, which means the effect of reinforced measures for slope stability enhancement is obvious. More specifically, the combined reinforcement measures including surface treatment and bio-pile has a more significant effect on improving the stability of slope.

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