Stability Reinforcement of Slopes Using Vegetation Considering the Existence of Soft Rock

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Abstract: This study investigates the effectiveness of vegetation reinforcement on the stability of a slope with red-bed soft rock in a slope along the Xining-Chengdu railway, China. Four kinds of vegetation were considered to reinforce the soil and the slope. The rooted soil parameters were determined based on the laboratory tests. A numerical model was developed based on the actual geometry and soil layer distributions. The soils were modeled as elastic perfectly plastic materials and the vegetation reinforcement was represented as addition cohesion of a series of subsoil layers within a given depth. The effectiveness of vegetation on slope reinforcement under both dry and rainfall conditions was investigated regarding this case. The potential failure surface and corresponding factor of safety of the red-bed soft rock slope for those different conditions were analyzed and compared. It has been found that the addition of vegetation increased the safety of slope stability whether the slope is under a dry condition or a rainfall condition, while the increasing proportion of factor of safety due to vegetation reinforcement for this case is very limited. The results and findings in this study are still significant for the practitioner to evaluate the reasonability of vegetation reinforcement.

Keywords: soil reinforcement; vegetation; red-bed soft rock; rainfall; finite element method

1. Introduction

Slope stability is one of the very traditional but significant issues related to geotechnical engineering, embankment engineering, dam engineering and landfill engineering [1–6]. Due to the catastrophic consequence caused by slope failure, many reinforcement methods have been developed, such as drainage systems [7], stabilizing piles [8], reinforcement of vegetation, among others. Due to its environmentally friendly characteristics compared to soil nails, geosynthetics, retaining structures, gabions and shotcrete, the reinforcement of vegetation, such as grass and shrubs, on the slope stability, has been gradually recognized [9–20], and there are an increasing number of slope protection engineering with vegetation grew on the slope in recent years [19–28]. In fact, vegetation-soil interaction and plant-soil-atmosphere interaction are rather complex, thus the mechanism and effectiveness of vegetation reinforcement on slope stability are significant and it has attracted much attention of researchers.

In the past two decades, investigations on the effects of vegetation on slope stability have been widely conducted [12,29–34]. Among these studies, some of the studies focus on how the soil properties changed due to the existence of vegetation roots. For instance, additional cohesion due to vegetation reinforcement was investigated and determined through direct shear tests [35–37]; and both additional cohesion and increased friction angle caused by root reinforcement were determined by using triaxial tests [38,39]. It has been reported that the vegetation also affected the tension strength of partially saturated...
soils [40]. Dias, et al. [41] have reviewed the methods for evaluating the root reinforcement for slope stability using both limit equilibrium method numerical methods, and Leung, et al. [42] reviewed the contribution of shrub and tree roots on slope stability under both dry and wet conditions in Hong Kong. Moreover, several studies have been carried out to understand how vegetation can improve slope stability. For instance, Genet, et al. [43] modified the root tensile resistance of different species growing on slopes to roots cellulose content. Kokutse, et al. [44] analyzed the effect of vegetation on slope stability based on the results of numerical simulation and concluded that slope angle shows the great effect of variations of the factor of safety (FS). However, the numerical analysis in this study was conducted based on a simplified and hypothetical slope. Su, et al. [45] investigated spatial variance in the distributions of roots and mechanical characteristics of Artemisia sacrorum for root reinforcement on the Loess Plateau of China. Lobmann, et al. [46] critically reviewed the slope stabilization potential of herbaceous vegetation as compared to woody vegetation and summarized the status of slope stabilization with herbaceous vegetation. Tsige, et al. [47] investigated the slope stability along a road by incorporating the effect of five types of plant roots through numerical modeling technique, and it was found that the factor of safety increased from 22–34% when the slope was reinforced with plant roots.

Even though the previous studies have demonstrated the effectiveness and mechanism of vegetation on increasing the stability of the slope, the investigation on the design and geotechnical application of vegetation reinforcement on actual engineering slope (e.g., red-bed slope) are still not enough [44], and most of the studies were conducted based on simplified or idealized soil slope. In addition, the effectiveness of the vegetation reinforcement on slope stability under rainfall conditions is still not clear. This paper aims at the effectiveness of vegetation reinforcement of the actual slope under both dry and rainfall conditions. A typical place along the Xining-Chengdu railway, China, has been experiencing slope instability issues and it served as a case in this study.

In this paper, four types of vegetation, i.e., grass, shrubs, young forest and mature forest, were considered to reinforce the slope in the case. The stability of the slope under various reinforcement and rainfall conditions was analyzed by using the finite element software Plaxis 2D. The effect of vegetation root was simplified as the addition cohesion of the soils. The numerical results for the various conditions were compared to study the effect of vegetation type on slope stability. It has been found that the vegetation reinforcement indeed increased the safety of slope stability for the dry and rainfall situations, while the increasing proportion of factor of safety (FS) was not large because the vegetation root didn’t intersect the relative deeper potential slip surface.

2. Materials and Methods

2.1. Project Background and Site Description

The Xining-Chengdu Railway is located at the junction of Qinghai, Gansu and Sichuan provinces in China. It is an important railway passage connecting Sichuan, Gansu and Qinghai, also a necessary passage connecting northwest to southwest and south China. The overall line runs from north to south, starting from the Xining Basin in the northeastern part of Qinghai Province in the north, passing through the Qilian Mountains, the Qinling Mountains and the Ruogai grassland, and finally reaching the Minshan Mountains. It is connected to the Chenglan Railway in Songpan County, Sichuan Province, with a total length of about 509 km. This paper analyzes a specific site along the railway, which is located in Ganjia Township, Xiahe County, as shown in Figure 1. It is a hilly area on the edge of a piedmont alluvial basin. Some positions of the site are covered by grass. The ground elevation is 3163–3185 m, and the relative height difference is about 22 m. The project area is characterized by a humid monsoon climate in the cold plateau zone, with an average annual rainfall of 468.7 mm, mostly from May to October. The annual average evaporation is 1382.3 mm, and the annual average temperature is 3.7 °C, with the annual maximum and minimum temperature up to 30.7 and −26 °C, respectively.
Figure 1. The position, geometry and status of the case in this study.

Based on the drilling boreholes, the typical distributions of the soil layers in this area are characterized and determined. Figure 2 shows that the site mainly comprises sandy loess, silt and mudstone, which is a typical kind of red-bed soft rock. Sandy loess is distributed on the surface of the site, with a thickness of about 2.0–16.0 m. Sandy loess in this site is light yellowish-brown and mainly composed of silty grains. The soil is relatively uniform, containing a small number of clay particles, occasionally scattered gravel and a small amount of needle-like pores locally. In contrast, the silt in this site is distributed within thin layers, with a thickness of about 2.0–5.8 m. It is light brown-yellow and mainly composed of powder particles, containing a small number of clay particles. The soil is relatively uniform, and a few rusty yellow stripes can be seen. Furthermore, mudstone is yellowish-brown, light brownish-red and is mainly composed of clay minerals, with poor diagenesis and weak cementation. The detailed parameters of the physical and mechanical properties of sandy loess, silt and red mudstone that may largely influence the slope stability in the site are given in Tables 1 and 2 and Figure 3. Note that all these parameters are obtained via conventional laboratory tests with the samples from boreholes at Ganjia Township, Xiahe County (see Figure 2). Heating by the oven is used to test the natural water content, fall cone test is used for the Atterberg limits, whereas the cohesion and friction angle are obtained using direct shear tests. All laboratory tests procedures follow the standard GB/T 50123-1999.
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Figure 2. Geological conditions of the site based on drilling-hole tests.

Table 1. Basic properties of the sandy loess and silts.

| Soil Properties                  | Unit        | Max   | Min   | Avg   | Max   | Min   | Avg   |
|----------------------------------|-------------|-------|-------|-------|-------|-------|-------|
| Natura moisture content          | %           | 16.900| 4.200 | 10.068| 22.900| 18.000| 20.600|
| Natural density                  | g/cm³       | 1.840 | 1.430 | 1.570 | 1.890 | 1.720 | 1.820 |
| Dry density                      | g/cm³       | 1.590 | 1.320 | 1.430 | 1.560 | 1.400 | 1.510 |
| Void ratio                       | %           | 1.049 | 0.694 | 0.892 | 0.929 | 0.729 | 0.791 |
| Water saturation                 | %           | 63.800| 13.500| 29.879| 78.700| 63.900| 70.480|
| Liquid limit                     | %           | 26.500| 24.900| 25.497| 26.100| 25.400| 25.700|
| Plastic limit                    | %           | 17.300| 16.200| 16.641| 16.700| 16.500| 16.620|
| Plastic index                    | -           | 9.500 | 8.400 | 8.856 | 9.400 | 8.800 | 9.080 |
| Liquid index                     | -           | 0.010 | −1.450| −0.744| 0.690 | 0.160 | 0.438 |
| Cohesion                         | kPa         | 17.2  | 16.3  | 16.8  | 16.3  | 18.8  | 18.1  |
| Friction angle                   | degree      | 21.6  | 19.4  | 20.7  | 20.6  | 18.8  | 19.4  |

Table 2. Mechanical parameters and values for the numerical model.

| Soil Layer    | Dry Density | Young's Modulus | Poisson Ratio | Shear Modulus | Cohesion | Friction Angle |
|---------------|-------------|-----------------|---------------|---------------|----------|---------------|
|               | Unit kg/m³  | kPa             | /             | kPa           | kPa      | degree        |
| Sandy loess   | 1430        | 11,500          | 0.3           | 4423          | 16.8 a   | 20.7 a        |
|               |             |                 |               |               | 16.3 b   | 19.4 b        |
| Silt          | 1510        | 10,800          | 0.35          | 4000          | 18.1 a   | 17.8 b        |
|               |             |                 |               |               | 19.4 a   | 18.8 b        |
| Mudstone      | 2250        | 411,030         | 0.23          | 167,085       | 112.6    | 34.3          |

Note: superscripts a and b denote average value and minimum value, respectively.

To ensure the safety of the railway, some measures may be taken to avoid the potential slope instability in these zones, although the maximum slope angle of the typical slope section is 33 degrees. As discussed above, vegetation reinforcement is one of the feasible ways to ensure the safety of the slope. To further testify the effectiveness of the vegetation reinforcement, including the partially covered grass, on the slope stability, in this case, a series of numerical simulations are performed, as discussed in the following sections.
Table 1. Basic properties of the sandy loess and silts.

| Soil Properties    | Unit | Sandy Loess | Silt |
|--------------------|------|-------------|------|
| Maximum moisture content (%) | 16.900 | 22.900 | 18.000 |
| Natural density (g/cm³) | 1.840 | 1.890 | 1.720 |
| Dry density (g/cm³) | 1.590 | 1.560 | 1.400 |
| Void ratio (%) | 1.049 | 0.929 | 0.729 |
| Water saturation (%) | 63.800 | 78.700 | 63.900 |
| Liquid limit (%) | 26.500 | 26.100 | 25.400 |
| Plastic limit (%) | 17.300 | 16.700 | 16.500 |
| Plastic index | 9.500 | 9.400 | 8.800 |
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| Soil Layer | Dry Density (kg/m³) | Young’s Modulus (kPa) | Poisson Ratio | Shear Modulus (kPa) | Cohesion (kPa) | Friction Angle (degree) |
|------------|---------------------|-----------------------|---------------|---------------------|----------------|-------------------------|
| Sandy loess | 1430                | 11,500                | 0.3           | 4423                | 16.8           | a 16.3 b 20.7 a 19.4 b |
| Silt       | 1510                | 10,800                | 0.35          | 4000                | 18.1 a 17.8 b 19.4 a 18.8 b |
| Mudstone   | 2250                | 411,030               | 0.23          | 167,085             | 112.6          | 34.3                    |

Note: superscripts a and b denote average value and minimum value, respectively.

Figure 3. Variations of properties of mudstone with sample depth determined from laboratory.

2.2. Numerical Model and Simulation

2.2.1. Reinforcement of Vegetation on Soil Strength

The contribution of vegetation roots in the shear resistance of the soil is often taken as an additional cohesion of the soils [44,48]. The increase of soil shear strength due to root reinforcement can be expressed as [48]:

\[ C = t_R (\cos \theta \tan \varphi + \sin \theta) \]  

where \( t_R \) denotes the unit tension strength of the vegetation root; \( \theta \) denotes the shear rotation angle, equaling to 90-slope angle (degree); \( \varphi \) denotes the friction angle of the soil.

Four types of vegetation were considered in this study to reinforce the slope stability: grass, shrubs, young forest and mature forest, as shown in Figure 4a. The increase of soil shear strength caused by root reinforcement was represented as the increase of soil cohesion, which was further given as a function of depth to reflect its variations with depth. In this study, the influence of vegetation root on soils shear strength was considered only within a depth of 2.0 m, and a total of 6 sub-layers (0–0.25 m, 0.25–0.5 m, 0.5–0.75 m, 0.75–1.0 m, 1.0–1.5 m, 1.5–2.0 m) were divided with each of sub-layer characterized by a typical increase value of soil cohesion, similar to those in [44]. Such a subdivision of layers is to ensure quantitative consideration of reinforcement on soil strength by different types of vegetation and guarantees simultaneously the differences among them, as reported in [44]. The detailed increase value for the four vegetation was illustrated in Figure 4b. The influence depths of the grass, shrubs, young forest and mature forest are 0.25, 1.0, 1.5 and 2.0 m, respectively.
2.2.2. Numerical Model Development

In this study, the slope characterized by red-bed in this site with a size of 113 m long and 59 m high was modeled using the 2D finite element program PLAXIS [49]. To consider the effect of root vegetation, six layers on the top of the geometry were divided. The mesh of the numerical model was generated using the triangular element, with local mesh refinement in some parts of the geometry. The 15-node triangle was used due to its fourth-order interpolation for displacements and 12 Gauss points for numerical integration. The mesh distributions of the model were presented in Figure 5, with a total of 5380 elements and 43,837 nodes. The bottom boundary was blocked, with both the horizontal and vertical displacements not allowed. The left and right boundaries of the slope were restrained in the horizontal direction. The top boundary of the slope was normally set as traction-free. However, a surcharge load with a value of 600 Pa due to the presence of trees was applied on the top, which corresponded to the cases of plants of young forest and mature forest with a plantation density of 350 trees/ha [50]. In addition, a rainfall intensity of 10 mm/day (light rain) or 50 mm/day (heavy rain) was also considered for the cases that analyze the slope stability under rainfall conditions. No groundwater table was detected in the borehole within a depth of 25 m during the geotechnical survey in dry seasons. For the convenience of seepage analysis and considering the effect of wet seasons, the groundwater level for the numerical model was set as 6 m above the bottom of the numerical model.

Mechanical properties of the three soils were represented using the elastic perfectly plastic Mohr-Coulomb constitutive failure criteria. The detailed parameters of the three soils were listed in Table 2. Noticeably, both the average and minimum value of the sandy loess and silts were adopted to investigate the stability of the slope. The hydraulic conductivity of the three soils is also necessary to analyze the stability of the slope with rainfall. The saturated hydraulic conductivity of the sandy loess, silt and mudstone are determined as $1.05 \times 10^{-6}$, $0.258 \times 10^{-6}$, $1 \times 10^{-10}$ m/s, respectively, based on the constant head experiments during the geotechnical investigation report on this site. Van-Genuchten function [51] is adopted to describe the water retention behaviors of the soils, which can be further used to determine the relative hydraulic conductivity of soils. The detailed hydraulic parameters for the numerical model implemented in Plaxis 2D are listed in Table 3.

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Figure 4. Root reinforcement: (a) four different vegetation; (b) Relationships between root additional cohesion and depth (modified from Kokutse et al. (2016)).
Mesh distributions with the root reinforcement of the numerical model.

**Figure 5.** Mesh distributions with the root reinforcement of the numerical model.

**Table 3.** Parameters for Van Genuchten function of the three soils.

| Soil Layers | Saturated Moisture Content | $\alpha$ | $l$  | $n$  |
|-------------|---------------------------|---------|------|------|
| Unit        | %                         | m$^{-1}$| /    | /    |
| Sandy loess | 47%                       | 1.360   | −0.8030 | 1.342 |
| Silt        | 46%                       | 0.94    | −1.382 | 1.400 |
| Mudstone    | 55%                       | 2.24    | −0.300 | 2.286 |

The factor of safety (FS) of the slope with or without vegetation reinforcement was determined using the strength reduction method (SRM), which successively reduced both the cohesion and friction of the soils while keeping the internal stress field of the slope constant, to cause the failure of the slope [52,53]. The value of $\Sigma$Msf at failure in the Plaxis program indicates the FS of the slope at the current state [49].

**2.2.3. Simulation Scenarios**

To investigate the effect of vegetation type and reinforcement on the stability of the slope, in this case, a total of 15 simulation cases with various rainfall situations were conducted. Those simulations can be divided into two groups: one for stability analysis with rainfall while the other with various intensities of rainfall. The vegetation reinforcement was set by increasing the cohesion with various values for the six sub-layer soils. Comparisons of reinforcing effect by different vegetation types were also conducted based on the simulation results for both dry and rainfall conditions. For the cases with and without vegetation reinforcements, only additional cohesion was applied in the case with vegetation reinforcement and other input parameters are the same.

Before the simulation, a constant gravitational load is applied to generate geostatic stress. For a slope with a constant groundwater level and no rainfall/evaporation on the surface, the distribution of matric suction above the groundwater level is linear, but the matric suction head of the natural slope generally has an upper limit. Generally, a minimum infiltration rate is given on the surface of the slope to obtain a steady-state, which can ensure a relatively reasonable suction distribution and can be set as the initial state of the rainfall cases. Thus, for the cases with rainfall in this example, we first prescribe virtual precipitation of 1 mm/day on the upper surface of the slope and calculate the steady-state of the seepage. Then, the steady-state was taken as the initial state for the rainfall-induced deformation of the slope.
3. Results

3.1. Effect of Vegetation on the Slope Stability without Rainfall

Figure 6 depicts the results of FS calculated using average soil strength parameters for the case without vegetation reinforcement and rainfall. The total displacement contour and incremental deviatoric stress corresponding to the failure state using the SRM technique indicate the failure mode and slip zones of the slope. The slope failure, in this case, will most likely occur within the left top zone, in which the slope is relatively steeper than that in the right top zones. The right curve in the figure points out that the FS of this case is 1.627, demonstrating that the slope is in a safe state.

The comparison of reinforcement results on the slope of the four types of vegetation is given in Figure 7. Note that the results obtained using both the average and the minimum soil strength parameters are given simultaneously. All FSs calculated using the four vegetation reinforcement are larger than those without vegetation. However, the increment of FS concerning grass and shrubs reinforcement is small in this case, definitely different from those obtained in [44,47]. The reason may be that the potential sliding surface, in this case, is much deeper, so that the cohesion increase within a depth of smaller 2 m does not resist the slip of the slope to a large extent. The FS for the case with forest reinforcement is larger than that without vegetation, which indicates that young forest and mature forest are more effective to increase the slope stability than grass and shrubs for dry conditions. The increased stability of forests can be attributed to both the larger cohesion increase and the deeper root zone. In Plaxis, the tension cut-off denotes the small tensile stress in soils when using the Mohr-Coulomb constitutive model. The tension cut-off zones (white points in the figure) for the cases of grass and shrubs are larger than those of forest, further indicating the more effectiveness of forest. By comparing the results of Figure 7a,b, FS values calculated using average soil strength parameters are 0.07 larger in value than those using minimum soil strength parameters. The difference should be given more attention in practice. It also indicates that the reliability of the slope stability is significantly valuable due to the variations of the soil parameters in spatial [54].
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Figure 7. Comparison of the four type of vegetation on reinforcement of the slope: (a) using average soil strength parameters; (b) using minimum soil strength parameters. Note: the red and white points denote the plastic point and tension cut-off point of the slope during the calculation of the factor of safety.

The relative increase of FS with different vegetation reinforcement for this case is illustrated in Figure 8. Note that the increased proportion of FS due to grass, shrubs, young forest and mature forest are 7.1%, 13.6%, 17.1% and 18.7%, respectively, in the study of Kokutse, Temgoua and Kavazovic [44], which are much larger than those in this case. The reason may be that the relatively shallow slip surface in that study is much more influenced by the reinforcement of the vegetation.
3.2. Effect of Vegetation on the Slope Stability with Rainfall

The suction distributions on different days during the rainfall for the case without vegetation reinforcement are presented in Figure 9. With the continuous rainfall, the suction on the top surface gradually decreased from 10 to 0 kPa, which also demonstrated that the water flowed into the subsoil layers due to rainfall. The zones with relatively small suction also indicated the zones with relatively high moisture content. Comparing the cases with different rainfall intensities, the larger rainfall intensity corresponded to the larger moisture content at the same zone.

Figure 10 presents incremental deviatoric strain corresponding to failure during FS calculation and total displacement on different days during the rainfall for the case without vegetation reinforcement. It is no doubt that the larger rainfall time caused relatively smaller FS with the same rainfall intensity, and the larger rainfall intensity induced the relatively smaller FS with the same rainfall volume. In other words, the stability of the slope gradually reduced with the increase of infiltration of water due to rainfall. For the case with a rainfall intensity of 10 mm/day, it should be noted that the total displacement on the 20th day was much larger than those on the 4th day. The reason for this phenomenon may be that the pore pressure on the 20th day was much larger than that on the 20th day, which induced a much smaller effective stress of the soil matrix and a larger deformation of soils. Similarly, for the case with a rainfall intensity of 50 mm/day, the total displacement on the 20th day was larger than that on the 2nd day. However, the positions of the larger total displacement on the two different moments are not the same, demonstrated that the positions or zones for the maximum deformation have changed from the 2nd day to the 10th day. The reason may be that the continuous heavy rainfall has accumulated on the relatively flat platform, which not only decreased the effective stress on that position but also increased the water self-loading due to rainfall.
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The effect of the vegetation on FS of the slope with different rain flow conditions and soil strength parameters is presented in Figure 11. Overall, the FS of the slope decreased evidently with the rainfall. The reinforcement of vegetation evidently increased FS of slope compared to that without vegetation under the same rainfall conditions, also demonstrating that the effectiveness of vegetation reinforcement under rainfall conditions. The increasing extent of the FS contributed by young forest and mature forest are much larger than those contributed by grass and shrubs. Interestingly, the FS for the case with rainfall intensity of 10 mm/day on the 4th day was larger than that on the 1st day, which may be caused by the transfer of slip surface due to rain infiltration. Comparing the results using the average and the minimum soil strength parameters, it can be further testified that using average soil strength parameters may be unsafe due to the variations of soil parameters in spatial. The necessity of using random field and reliability theory for the evaluation of slope stability has been emphasized by various scholars in the past three decades [55,56]. For the case of rainfall intensity of 50 mm/day, FS calculated on the 10th day obviously decreased, which was caused by the continuous heavy rain and the accumulation of water on the surface of the slope, as illustrated in Figure 10. Even though this kind of continuous heavy rain is infrequent in the position of this case, it should be noted the extreme rainfall would largely reduce the safety of the slope, which may even give threatens to the normal service of the railway.

Figure 9. Distribution of suction within the slope on different days during the rainfall for the case without vegetation reinforcement: left with a rainfall intensity of 10 mm/day and right with a rainfall intensity of 50 mm/day.
Figure 9. Distribution of suction within the slope on different days during the rainfall for the case without vegetation reinforcement: left with a rainfall intensity of 10 mm/day and right with a rainfall intensity of 50 mm/day.

Figure 10 presents incremental deviatoric strain during FS calculation and total displacement on different days during the rainfall for the case without vegetation reinforcement. It is no doubt that the larger rainfall time caused relatively smaller FS with the same rainfall intensity, and the larger rainfall intensity induced the relatively smaller FS with the same rainfall volume. In other words, the stability of the slope gradually reduced with the increase of infiltration of water due to rainfall. For the case with a rainfall intensity of 10 mm/day, it should be noted that the total displacement on the 20th day was much larger than those on the 4th day. The reason for this phenomenon may be that the pore pressure on the 20th day was much larger than that on the 20th day, which induced a much smaller effective stress of the soil matrix and a larger deformation of soils. Similarly, for the case with a rainfall intensity of 50 mm/day, the total displacement on the 20th day was larger than that on the 2nd day. However, the positions of the larger total displacement on the two different moments are not the same, demonstrated that the positions or zones for the maximum deformation have changed from the 2nd day to the 10th day. The reason may be that the continuous heavy rainfall has accumulated on the relatively flat platform, which not only decreased the effective stress on that position but also increased the water self-loading due to rainfall.

Further, the increase of FS of the slope with different rain flow conditions and soil strength parameters is presented in Figure 12. The horizontal dash in these figures denotes the initial FS without vegetation reinforcement. It is more apparent that the addition of vegetation more or less increased the FS of the slope for different rainfall cases. Reinforcement of slopes using vegetation can be a feasible way to enhance the stability of the slope. However, the FS increase caused by mature forest and the young forest is not always larger than the increase caused by grass and shrubs. The significant findings should be given more attention when using vegetation for the reinforcement of slope in practice. In addition, the increasing proportion for various rainfall conditions also positively or negatively varied with the rainfall time. This also indicated that the increase of FS due to vegetation reinforcement is dependent on the actual situation of the slope.
Figure 10. Incremental deviatoric strain during FS calculation and total deviatoric strain for different rainfall conditions and soil strength parameters: (a) 10 mm/day rainfall and average soil strength parameters; (b) 10 mm/day rainfall and minimum soil strength parameters; (c) 50 mm/day rainfall and average soil strength parameters; (d) 50 mm/day rainfall and minimum soil strength parameters.

Figure 11. Factor of safety of the slope with different rainfall conditions and soil strength parameters: (a) 10 mm/day rainfall and average soil strength parameters; (b) 10 mm/day rainfall and minimum soil strength parameters; (c) 50 mm/day rainfall and average soil strength parameters; (d) 50 mm/day rainfall and minimum soil strength parameters.

Figure 13 depicts the comparison of FS for different cases without rainfall and with a rain amount of 100 mm. Obviously, FSs for the cases without rainfall are evidently larger than those for the cases with rainfall, no matter what a heavy rain or a light rain. For the case without vegetation reinforcement, the FS value calculated for the case with larger rainfall intensity (50 mm/day) is smaller than that calculated for the case with smaller rainfall intensity (10 mm/day). This is following the fact that the temporary heavy rain is more dangerous for slope stability. However, for the cases with vegetation reinforcement, FS for the heavier rainfall case is not always larger than that for the smaller rainfall cases, which demonstrated that the addition of vegetation has changed the potential slip mode, compared to that without vegetation. Furthermore, in terms of the four types of vegetation, it seems that the effectiveness of shrubs is not better than that of grass, which may be attributed to that the increase of both cohesion and influencing the depth of shrubs root has changed the potential sliding surface. Similarly, the effectiveness of a mature foresee is not always better than that of a young forest. These phenomena indicate that the reinforcement effect of the four vegetation is not proportional to their cohesion addition and influencing depth. In practice, the design of vegetation reinforcement should be analyzed in advance, and it does not match the expectation that the deeper the reinforcement depth is, the safer the slope is.
Further, the increase of FS of the slope with different rain flow conditions and soil strength parameters is further depicted in Figure 14. The more closer the point is to the diagonal dash line, the more closer the proportion of FS increase using average and minimum soil strength parameters, which is the safer the slope is.

Figure 12. Increase of factor of safety of the slope with different rainfall conditions and soil strength parameters: (a) 10 mm/day rainfall and average soil strength parameters; (b) 10 mm/day rainfall and minimum soil strength parameters; (c) 50 mm/day rainfall and average soil strength parameters; (d) 50 mm/day rainfall and minimum soil strength parameters.

Figure 13. Comparison of the factor of safety for the cases with accumulative rainfall amount of 100 mm and no rainfall using both average and minimum soil strength parameters.

Comparison of the FS increase proportion using average and minimum soil strength parameters is further depicted in Figure 14. The more closer the point is to the diagonal dash line, the more closer the proportion of FS increase using average and minimum
The results of FS increase due to vegetation reinforcement for the cases with and without rainfall are further depicted in Figure 15. Generally, all the vegetation additions have increased the slope stability. Compared to the results of young and mature forests, the increasing range of grass and shrubs are relatively smaller, demonstrating that the young forest and mature forest have the potential to largely increase the safety of the slope stability. In addition, although the rainfall has decreased the safety of the slope stability, it didn’t obviously affect the increase of FS due to vegetation reinforcement.

![Figure 14](image1.png)

**Figure 14.** Comparison of the FS increase proportion using average and minimum soil strength parameters.

4. Discussion

The addition of vegetation indeed increases the slope stability of the slope in this engineering case due to the presence of the root in soils, however, the increasing proportion is relatively low, which is largely different from that in [44,47]. The increasing proportion of FS can be even large closing to 20% for the mature forest reinforcement. This kind of difference is mainly caused by the different slope failure mechanisms. For the slope
in [44,47], it would tend to be a failure with a shallow slip surface, and the vegetation root increases the cohesion of soil around the potential slip surface, which in turn makes the slips surface shift deeper below the ground surface. As a consequence, the FS of the slope substantially increases due to the reinforcement of the vegetation. While for the slope in this actual case, the potential slip surface is in a relatively deeper position, which is beyond the extent of the root zone. So modifying the type of vegetation seems to not contribute to a large increase in FS. In order to ensure the effectiveness of vegetation reinforcement, the root of the vegetation should cross the potential slip zones. In addition, to prevent the failure of the slope, the cohesion addition due to vegetation root in the potential slip zones should be sufficient to resist the failure of the soils in these zones.

The results calculated using minimum soil strength parameters are much smaller than those calculated using the average soil strength parameters. Given the spatial variability of the soil strength parameters, using minimum soil strength parameters evidently underestimates the safety of slope stability, while using average soil strength parameters may overestimate or underestimate the safety of slope stability. That is, the reliability of the safety of the slope stability is significant to give a reasonable and scientific evaluation of the slope stability. Moreover, the cohesion addition of soil due to vegetation reinforcement is dependent on the density of the roots, the length of the root, the porosity of the soil and other influencing factors, which leads to the relatively larger spatial uniformity of the cohesion addition when taking vegetation reinforcement into account. As a consequence, the effect of the variability of the cohesion addition due to vegetation reinforcement should also be considered during the analysis and evaluation of the slope stability. The reliability of the stability of the traditional slopes has been investigated by various scholars, while the related studies on the reliability of vegetation reinforcement on slope stability are still rare, which should be given more attention in the future.

Actually, the effect of vegetation on slope stability is not only dependent on the cohesion addition of roots on soils but also influenced by the change of water seepage path due to the existence of root systems [26,57,58]. It has been recognized that the soil permeability was dependent on the age of the vegetation root, and mature or decaying roots generally increased the soil permeability [59]. Laboratory results indicated that vegetation roots also influenced the water retention behaviors of soils [60]. Moreover, soil suction can be changed due to the enhanced evaporation caused by vegetation roots, especially on summer days [61]. Consequently, in the situation of rainfall, the vegetation root may affect the water flow; while in the situation of dry weather, the moisture may be absorbed by the root for its growth. Both of the aforementioned situations will make the redistribution of the moisture compared to that without vegetation, which in turn changes the distribution of pore water pressure and capillary pressure and eventually affects the effective stress of the soil matrix [57]. As it is known, slope stability is basically determined by the effective stress of the soil matrix within the slope, thus those factors can definitely influence the slope stability of the soils when it comes to vegetation reinforcement. Capobianco, et al. [62] have evaluated the vegetation reinforcement using SEEP/w by considering both the cohesion addition and the potential evapotranspiration, which provides a feasible way to consider the coupled hydro-mechanical reinforcement of vegetation. Even though permeability change due to vegetation roots has also been incorporated to investigate the reinforcement effectiveness on soil slope stability [62], more investigations on the permeability change due to vegetation roots should be conducted to further quantitative describe their relations. Overall, the effect of the vegetation root on the distribution of moisture content is much less, although some scholars have recently investigated the coupled interaction between the soil, moisture and vegetation root [57,63,64]. In addition, the experimental results demonstrated that the integrated friction angle increased up to a maximum value of 40 degree due to the existence of vegetation root [39]. Hence, the effect of vegetation on slope stability should be further studied in a more general way which should take not only the effect of the root on cohesion addition of soils but also the moisture redistribution due to the existence of root, as well as their relations with root profiles [65].
5. Conclusions

The effectiveness of vegetation reinforcement on slope stability with the red-bed soft rock of a case study in Xicheng railway, China was evaluated. The reinforcement of vegetation roots was expressed by the additional cohesion of soils in shallow soil layers. The stability of the slope reinforced by grass, shrubs, young forest and mature forest under normal or rainfall conditions was modeled and analyzed. Based on the results of the numerical simulation, the following conclusions can be drawn.

1. The addition of vegetation indeed increased the safety of slope stability, whether the slope is under a dry condition or a rainfall condition. The effectiveness of young and mature forests is basically more effective to increase the slope stability compared to that of grass and shrubs, although the young and mature forest leads to a surcharge to the slope.

2. The stability of the slope gradually reduced with the increase of infiltration of water due to rainfall. The increasing proportion due to vegetation reinforcement for various rainfall conditions positively or negatively varied with the rainfall time, indicating that the increase of FS due to vegetation reinforcement is dependent on the current situation of the slope. With the same amount of rainfall for the case without vegetation reinforcement, the FS value calculated with larger rainfall intensity (50 mm/day) is smaller than that calculated with smaller rainfall intensity (10 mm/day). For the case with vegetation reinforcement under the same rainfall volume, FS for the heavier rainfall case is not always larger than that for the smaller rainfall cases, demonstrating that the addition of vegetation has changed the potential slip mode and surface, compared to that without vegetation.

3. In this case, the critical slip surface is much deeper, which resulted in that the reinforcement effect of the four vegetation are not proportional to their cohesion addition and influencing depth. It does not match the expectation that the deeper the reinforcement depth is, the safer the slope is. In practice, the design of vegetation reinforcement should be analyzed in advance.

4. Compared to the slopes with shallow potential slip surfaces, the increase of FS due to vegetation reinforcement for this case is very limited. The reason is that the rather deeper critical slip surface was not intercepted by the vegetation root, even for the mature forest, which failed to provide enough shear resistance for the soil around the slip surface. For the specific case, the effectiveness of vegetation reinforcement should be evaluated in advance. If the depth of the potential slip surface is over the maximum depth of the vegetation root, it may be not appropriate to use vegetation as a way of slope reinforcement.

5. Using average or minimum soil strength parameters may overestimate or underestimate the safety of the slope due to the variations of soil parameters in spatial. It is necessary and significant that using random field and reliability theory for the evaluation of slope stability. The spatial variability of the additional cohesion due to vegetation is also meaningful to reasonably evaluate the safety of slope stability.

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