The Influence of Rainfall and Evaporation Wetting–Drying Cycles on the Open-Pit Coal Mine Dumps in Cam Pha, Quang Ninh Region of Vietnam

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Abstract: Among the slope hazards caused by rainfall, not all of them occur directly during storm washout, and the wetting–drying cycles’ effect on the rainfall–evaporation process is an important cause of shallow slope instability. In this study, taking the slope of the open-pit coal mine dumps in Cam Pha, in the Quang Ninh region of Vietnam, as the research object, we carry out experiments on the physical properties of the rock body under different wetting–drying cycles, as well as numerical analyses. The results show that the wetting–drying cycles significantly affect the physical and mechanical parameters and permeability of the rock body. In the process of the wetting–drying cycle, a transient saturated zone occurs on the surface of the slope, and the range of the unsaturated zone inside the slope body decreases with the increase in the number of wetting–drying cycles. Moreover, the infiltration line keeps moving downward, but the rate of downward movement is slowed down by the decrease in the gradient of matrix suction affected by rainfall. Under the influence of the wetting–drying cycles, the slope displacement, plastic zone, and maximum shear strain increment range gradually approach the slope surface with the wetting–drying cycles, and the displacement peak gradually increases. A dump is a site for the centralized discharge of mining waste, formed by the crushing and stockpiling of the original rock formation. Bang Nau is the name of the dump considered in this study. After multiple rainfall events, the slope stability under five wetting–drying cycles decreases from 1.721 to 1.055, and the landslide mode changes from a whole landslide to a single-step shallow landslide, with a certain landslide risk. It is necessary to strengthen the slope stability as the landslide risk is very high, and it is necessary to strengthen the monitoring and inspection of the slope.

Keywords: open-pit mine; slope stability; dump; long-term wetting–drying cycles; rainfall intensity

1. Introduction

In regard to slope hazards, rainfall is the main cause of slope destabilization accidents, but not all destabilization accidents under actual engineering geological conditions occur directly during heavy rainfall washout. Moreover, the wetting–drying cycles’ effect on the rainfall–evaporation process is an important cause of shallow slope destabilization [1]. The open-pit mines in Vietnam are mainly located in the Cam Pha area of Quang Ninh Province, where long-term mining activities have resulted in the formation of numerous dumps. The dumps in the Cam Pha area are characterized by large heights and are usually constructed on slopes above the level of artesian drainage. In addition, the mine dumps in Cam Pha District, Quang Ninh Province, are located in the rainy area; in recent years, due to climate change, extreme weather has led to increased surface temperatures, heavy rainfall,
and storms, which have destroyed some of the retaining dams and led to the washing away of soil and rocks into the downstream areas, endangering the lives and property of hundreds of families. In the mines in Cam Pha District, Quang Ninh Province, due to the heavy and concentrated rainfall and abundant sunshine, slope soils undergo long-term wetting–drying cycles, resulting in the gradual development of pore cleavage [2,3], greatly reduced strength and deformation moduli [4], and altered physico-mechanical properties, which increase the likelihood of the occurrence of slope instability accidents. Therefore, it is necessary to analyze the influence of the wetting–drying cycle processes formed by rainfall and evaporation on the internal pore water pressure and stability of slopes to safeguard the normal mining activities in mines.

Many scholars have recognized the effects of wetting–drying cycles on the pore distribution, stress–strain relationships [5,6], and physico-mechanical properties of soils and have conducted extensive research on them. Ni et al. [7] studied the effect of the number of wetting–drying cycles on the development of cracks in soils and concluded that the size, shape, and arrangement of soil particles change after wetting–drying cycles [8]. Pardini et al. [9] investigated the effect of wetting–drying cycles on the volume changes of unsaturated soils [10]. Ye et al. [11] found that fracture development is an important reason for the reduction in soil strength after wetting–drying cycles. Hao et al. [12] concluded that a change in shear strength parameters is significantly correlated with the microstructural alterations resulting from wetting–drying cycle processes. Yuan et al. [13] concluded that wetting–drying cycles are an important reason for the instability of shallow portions of slopes. Lian et al. [14] concluded that the effect of wetting–drying cycles on the soil is an important indicator in the long-term stability analysis [15]. Mu et al. [16] investigated the permeability and soil–water characteristic curves of soil after wetting–drying cycles. Rui et al. [17] investigated the effect of wetting–drying cycles on the shear behavior of unsaturated compacted soils and concluded that the degree of wetting–drying and the normal stresses suffered have an important effect on the shear strength.

In addition, Gasmo et al. [18] used numerical modeling to study the variation in slope infiltration with the rainfall intensity and analyzed it to illustrate the effect of infiltration on slope stability. Ogila et al. [19] evaluated the slope stability under wetting–drying cycles based on the limit equilibrium method and finite element analysis. Khan et al. [20] used numerical analysis to simulate the slope stability and slope flow under wetting–drying cycles, and it was concluded that the softening of the soil caused by the process of wetting–drying cycles was the cause of slope damage [21]. Chou et al. [22] analyzed the seepage and stability of slopes with different gradients after wetting–drying cycles using the analysis software Geo-Studio 2018.

The above studies have confirmed the weakening effect of wetting–drying cycles on the microstructure and physical and mechanical properties of slope soil, and the study of the slope stability of open-pit mines under wetting–drying cycles is of great significance for the safety of actual production. However, the existing research results only consider the effect of wetting–drying cycles on the strength attenuation of the rock body, and not the effect of wetting–drying cycles on the infiltration characteristics of the soil. There are few reports on the combined effects of the transient stability of slopes on the soil strength and infiltration characteristics under the influence of wetting–drying cycles. Existing studies are not fully applicable to the wetting–drying cycle conditions suffered by the open-pit mine slopes in the Cam Pha area, Vietnam, so the modeling and simulation of the wetting–drying cycle conditions in the site during the dry and rainy seasons using the FLAC3D6.0 software would provide an important reference for the actual slope conditions in the area. In this paper, the stability of open-pit mine slopes under the influence of the rainy season in the Cao Son open-pit mine, in the Cam Pha area of Vietnam, is studied. A flow–solid coupling secondary development process and a numerical simulation scheme of wetting–drying cycles are established to study the effects of different rainfall cycles on the seepage flow field within the slope. We study the changes in the flow field, mechanical field, and slope stability coefficient in the slope during different periods of rainfall; reveal the mechanism...
of slope destabilization under different rainfall cycles; and analyze the slope stability and deformation by combining the change rule of slope displacement, the plastic damage area and form, and the maximum shear strain increment under different periods of wetting–drying cycles, to ensure that the open-pit coal mines in the rainy season in the Cam Pha area, Quang Ninh Province, display field stability.

2. Seepage Theory

2.1. Shear Strength Theory of Unsaturated Soil

The shear strength of the soil determines the stability of the slope, and Vanapalli et al. [23] proposed the following formula for the shear strength of unsaturated soil:

\[
\tau_f = [c' + (\sigma_n - u_a) \tan \phi'] + (u_a - u_w)(\frac{S - S_r}{1 - S_r}) \tan \phi'
\]

(1)

where \(\tau_f\) is the shear stress on the damaged surface when the soil body destroys/fails in the plane of the soil mass, kPa; \(c'\) is the effective cohesive force, kPa; \(\sigma_n\) is the normal stress, kPa; \(u_a\) is the pore gas pressure, kPa; \(\phi'\) is the effective internal friction angle, (°); \(u_w\) is the pore water pressure, kPa; \(\theta\) is the volumetric water content; and \(\theta_s\) is the saturated volumetric water content.

After transformation, the following equation can be obtained.

\[
\tau_f = [c' + (\sigma_n - u_a) \tan \phi'] + (u_a - u_w)(\frac{S - S_r}{1 - S_r}) \tan \phi'
\]

(2)

where \(\tau_f\) is the shear stress on the damaged surface when the soil body destroys/fails in the plane of the soil mass, kPa; \(S\) is the degree of saturation; and \(S_r\) is the degree of residual saturation. Thus, we have

\[
\tau_f = [c' + (\sigma_n - u_a) \tan \phi'] + S_c(u_a - u_w) \tan \phi'
\]

(3)

When the pore air pressure and pore water pressure are of the same magnitude, Equation (3) is the saturated shear strength equation [24], and the total cohesive force expression is [25]

\[
c_t = c' + S_c(u_a - u_w) \tan \phi'
\]

(4)

where \(c_t\) is the total cohesive force, kPa.

2.2. Seepage Theory of Unsaturated Soil

The unsaturated–saturated seepage equation [26] for the soil is

\[
q_i = -k_r(S)K_{ij}h_r = k_r(S)K_{ij}(\psi + \psi_z)\]

(5)

where \(q_i\) is the unit flow vector; \(k_r(S)\) is the relative permeability coefficient, and \(k_r(S) = 1\) in the saturated zone and \(0 < k_r(S) < 1\) in the unsaturated zone; \(K_{ij}\) is the permeability coefficient tensor; \(h_r\) is the hydraulic gradient; \(\psi\) is the pressure head, kPa; \(\psi_z\) is the position head, kPa; \(\gamma_w\) is the bulk weight of water, kN/m³; and \(u\) is the pore water pressure, kPa.

From Formula (1), it can be seen that saturated seepage and unsaturated seepage have the same expression, and soil-saturated seepage can be approximated as unsaturated seepage with saturation degree 1. The key to the study of unsaturated seepage in soils is to establish the relationship between the unsaturated seepage coefficient and the degree of saturation as a function of the matrix suction in the unsaturated zone, which, in practice, is expressed as negative pore water pressure.
The prediction of the unsaturated soil permeability coefficient uses the Van Genuchten–Mualem (VG–M) model [27], which is a combined form of the Soil–Water Characteristic Curve (SWCC) model and the permeability coefficient model [28] with the equation

\[ k_u = kS_0^{0.5}[1 - (1 - S_1^m)^m]^2 \]  

where \( k_u \) is the unsaturated permeability coefficient, m/s; \( k \) is the saturated permeability coefficient, m/s; and \( m \) is the fitting parameter.

2.3. Characterization of the Distribution of Substrate Suction

Matrix suction in an unsaturated soil layer in the natural state varies with depth, and the unsaturated flow in the vertical direction in the steady state conforms to Darcy’s law with the specific flow equation

\[ q = -k_u\left[\frac{d(u_a - u_w)}{\gamma_w}dz + 1\right] \]

where \( k_u \) is the unsaturated permeability coefficient of the soil associated with matrix suction.

The unsaturated permeability coefficient is a function of volumetric water content \( \theta \). The theoretical model of Gardner [29] can be solved for the characteristic parameters of seepage in saturated soils [30] by the equation

\[ k_u = k \exp[-\beta(u_a - u_w)] \]

where \( \beta \) is the rate of change in the soil permeability coefficient dependent on matrix suction, kPa\(^{-1}\).

Equations (7) and (8) combine to give

\[ q = -k \exp[-\beta \psi_h \gamma_w]\left[d\psi_h/dz + 1\right] \]

where \( \psi_h \) is the suction head.

The boundary condition \( z = 0 \), the suction force \( \psi_h = \psi_{h0} \), and the integration of Equation (9) are obtained:

\[ u_a - u_w = (-1/\beta) \ln[(1 + q/k) \exp(-\beta z \gamma_w) - q/k] \]

When the hydrostatic pressure condition is met, i.e., \( q = 0 \), the suction force is linearly distributed and there is

\[ u_a - u_w = z \gamma_w \]

2.4. Discounted Strength Method

In this paper, the strength discount method [31] is used for numerical calculations to solve the factor of safety, the soil cohesion and internal friction angle are discounted concerning the soil shear strength, and the expression is

\[
\begin{align*}
    c' &= \frac{c}{F} \\
    \phi' &= \tan^{-1}(\tan \phi/F) \\
    t' &= \frac{t}{F}
\end{align*}
\]

where \( c \), \( \phi \), and \( t \) are the cohesive force, Pa; internal friction angle, \(^\circ\); and tensile strength, Pa; \( c' \), \( \phi' \), and \( t' \) are discounted.

3. Finite Element Model Creation

3.1. Numerical Model for Slopes

The Cao Son open-pit mine is located in the north of Quang Ninh Province, Cam Pha City, Vietnam (Figure 1a,b). Presently, waste rock from the Cao Son coal mine is primarily
deposited in two dumping sites, Nam Khe Tam and Bang Nau, with Bang Nau being the principal site. According to the design specifications, the Bang Nau dumping site spans 2920 m in length and 1955 m in width, with the highest point of the site at an elevation of +300 m. As of 1 January 2019, the total volume of waste rock yet to be deposited at the Cao Son coal mine was 1.003532 billion cubic meters, of which 208.5 million cubic meters was directed to the Bang Nau dumping site, as shown in Figure 1c.

A numerical simulation geometric model was established based on the original geomorphic features and dumping parameters of the Bang Nau dump. The size of the established numerical computational model is 1150 m × 380 m. The dump consists of eight soil-discharging benches with a bench slope angle of 37° and a side slope angle of 23°.

3.2. Rainfall Condition

The Cao Son coal mining area falls within a tropical region characterized by high temperatures, humidity, and abundant rainfall. The year is divided distinctly into two seasons. The rainy season extends from April to October, with the highest recorded rainfall in a single year being 1411 mm in 2015, and with a total of 2916 mm over five months during the rainy season of the same year. The dry season spans from November of the previous year to March of the following year. Temperatures vary with the seasons, reaching highs of 37–38 °C in the summer months (July and August each year), while the winter temperatures typically range from 8 to 15 °C, occasionally dropping to 2–3 °C. The average humidity during the dry season is 65–80%, rising to 81–91%. Two factors, the rainfall intensity and rainfall duration in the tropics, cause various types of rainfall to exert different effects on slope stability. Generally, when the rainfall amount is certain, the rainfall manifests itself in two ways: short-duration strong rainfall and long-duration weak rainfall. To simplify the rainfall situation, the uniform type of long-term weak rainfall is selected. The simulation selects extreme rainfall data, i.e., the rainfall intensity is set to 47 mm/day, and the rainfall...
duration is 7 days. Observations of rainfall at the site show that the number of consecutive
days of rainfall is generally less than 7 days, so a rainfall cycle of 7 days was chosen for
this study. Under this rainfall intensity, the rainwater cannot penetrate the slope promptly,
and, therefore, water will inevitably accumulate at the surface after rainfall, resulting in a
sudden rise in the surface pore water pressure. The wetting–drying cycle simulation aims
to simulate the situation of multiple rainfall and rain stops, so the wetting–drying cycle
also needs to take into account the effect of the rain-stopping time on the slope. The change
in the seepage field is a slow and continuous process, as rain does not cause the seepage
field to produce an instantaneous change. At this time, the seepage field will produce a
hysteresis phenomenon, and the surface and slope out of the transient saturated zone will
slowly disappear. To eliminate the effect of rainout on the next cycle, and to ensure that the
distribution of the flow field in the slope is consistent in each cycle, the simulation of each
cycle is separated, and the simulation is reperformed in the next cycle.

3.3. Wetting–Drying Cycle Simulation Programs

Since matrix suction is also a type of force, which is manifested as a tensile effect
and will make the slope more stable, the effect of matrix suction cannot be neglected in
simulations. In the theory of unsaturated soil, matrix suction is negatively correlated
with the degree of saturation, and when the degree of saturation is 1, the matrix suction
will be reduced to 0. However, in unsaturated seepage, due to the defect of the software
itself, the degree of saturation of the region will be forced to be set to 1 when the matrix
suction, i.e., negative pore water pressure, is taken into account. Moreover, the degree
of saturation is related to the permeability coefficient of the rock, so the rainwater will
inflow according to the permeability coefficient of the completely saturated region when
the rainwater infiltrates. As saturation is related to the permeability coefficient of the rock,
the rainwater infiltration into the actual unsaturated zone will follow the permeability
coefficient of the fully saturated zone, which will make the numerical simulation results
inaccurate and counterintuitive. Therefore, when using the FLAC3D software to simulate
the seepage field in the slope and the slope stability under the influence of the seepage
field, it is necessary to carry out the secondary development of the software.

Based on the above unsaturated soil seepage theory, this numerical simulation firstly
imports the Bang Nau dump slope model, groups the slope model, sets the boundary
conditions, inputs the initial mechanical parameters and seepage parameters of each
stratum, and then runs the program to derive the distribution of the flow field in the slope
after a certain period. At this time, the saturation degree of each cell in the field is linked
with the unsaturated seepage coefficient, cohesion, and angle of internal friction through
a specific relationship equation to become a Fish function. Then, the negative pore water
pressure is taken into account, and the stability coefficient of the slope and the distribution
of the mechanical field are derived from the discounted strength method. In the next
step, the saturation degree of 1 regional unit through the Fish function is extracted and,
statistically, this saturation degree of 1 unit is assigned to the same group, and the water
level above the unsaturated area of distinction is determined. At this time, the water level
above the surface can be divided into two groups, a saturated group and an unsaturated
group. In the third step, the grouping of the second step is imported into the model, and
the physical and mechanical parameters of this cycle, such as the permeability coefficient,
water content, saturation, cohesion, etc., are corrected. The seepage field and mechanical
field changes are run and recorded. In the fourth step, we repeat the second and third steps
until we reach 5 cycles.

The flowchart of the wetting–drying cycle simulation scheme is shown in Figure 2.
3.4. Material Properties

The slope rock bodies in the study area are mainly the waste dump and bedrock, and the strength parameters of the slope rock and soil bodies are determined experimentally to determine the initial values. Experimental material was taken from the Bang Nau dump at the initial discharge in June 2020 (not experiencing rainfall). The specific parameters are shown in Table 1.

Table 1. Physical and mechanical parameters of slope rock mass.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Poisson's Ratio</th>
<th>Density/(g·cm⁻³)</th>
<th>Cohesion/(kPa)</th>
<th>Angle of Friction/(°)</th>
<th>Permeability Coefficient/(m·s⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Waste dump</td>
<td>0.31</td>
<td>1.83</td>
<td>47.23</td>
<td>17.32</td>
<td>8.7 × 10⁻⁸</td>
</tr>
<tr>
<td>Bedrock</td>
<td>0.29</td>
<td>2.05</td>
<td>104.54</td>
<td>26.21</td>
<td>9.8 × 10⁻¹⁰</td>
</tr>
</tbody>
</table>

Many studies have shown that the strength of the rock mass decays with the wetting–drying cycles. In this study, the cohesion, angle of friction, and permeability coefficient of the waste dump were tested for 5 cycles, and the results are shown in Table 2. Cohesion showed a slow decrease with the number of wetting–drying cycles, and the angle of friction showed no discernible pattern. The permeability coefficient showed a tendency to increase, stabilize and finally decrease with the number of wetting–drying cycles. Here, it is divided into three stages. The first stage of seepage will expand the existing fissures and form a large fissure with a rapid increase in the permeability coefficient ws. In the second stage, water will flow through the large fissure and only a small number of new fissures will be created, and the permeability coefficient ws increases slowly. In the third stage, water will break down the geotechnical body, blocking the seepage channels, and the permeability coefficient ws eventually decreases.
Table 2. Waste dump material strength at different wetting–drying cycle times.

<table>
<thead>
<tr>
<th>Number of Cycles</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cohesion/(kPa)</td>
<td>47.23</td>
<td>45.54</td>
<td>41.11</td>
<td>39.75</td>
<td>38.52</td>
<td>38.17</td>
</tr>
<tr>
<td>Angle of friction/(°)</td>
<td>17.32</td>
<td>17.27</td>
<td>17.39</td>
<td>17.31</td>
<td>17.25</td>
<td>17.21</td>
</tr>
<tr>
<td>Permeability coefficient/(m·s⁻¹)</td>
<td>$8.7 \times 10^{-8}$</td>
<td>$9.2 \times 10^{-8}$</td>
<td>$9.7 \times 10^{-8}$</td>
<td>$13.0 \times 10^{-8}$</td>
<td>$9.4 \times 10^{-8}$</td>
<td>$9.1 \times 10^{-8}$</td>
</tr>
</tbody>
</table>

3.5. Boundary Conditions

In the calculation of wetting–drying cycles for unsaturated soil slopes, the upper surface of the model is defined as a permeable boundary, and the surrounding area is defined as a non-permeable boundary. The perimeter of the slope model is set as a normal fixed constraint, and the geotechnical bodies on the surface of the slope model are free boundaries. Considering the mechanical properties of the dump and the scope of application of the constitutive model, the Mohr–Coulomb elastic–plastic model is selected for this simulation. The seepage model adopts the isotropic seepage model.

4. Slope Stability Analysis and Discussion

4.1. Pore Water Pressure

Since the first factor that causes changes during rainfall is the seepage field in the body of the slope, the mechanical field changes as the seepage field changes. Here, the flow field of the slope is analyzed first. Through the study of the seepage field within the slope, to understand the distribution of water pressure within the slope, a qualitative and quantitative analysis of the flow field of the slope body during rainfall is performed, which is mainly intended to study the positive and negative pore water pressure peaks and the regional distribution of the law of change. The change in the seepage field in the slope body after rainfall under different cycles is shown in Figure 3. The red area of Figure 3 represents the maximum value of the pore water pressure and the blue area represents the minimum value.

At 0 wetting–drying cycles, i.e., under the condition of no rainfall on the slope, the maximum positive pore water pressure within the slope was located at the bottom of the slope body. With the wetting–drying cycles, both the maximum positive pore water pressure on the slope surface and the maximum negative pore water pressure inside the slope body were increased, and the matrix suction gradually became smaller. This indicates that more and more water penetrates deeper into the slope with the drying cycle—not only into the surface layer but into the whole slope. From the peak zone of maximum positive pore water pressure on the slope surface until the value of pore water pressure is 0, i.e., matrix suction is 0, a transient saturation zone occurs. Below the transient saturated zone is the unsaturated zone; the extent of the unsaturated zone decreases with the number of wetting–drying cycles and the pore water pressure below the wetting front is redistributed according to a gradient. It can be inferred that the slope surface is the first to reach the saturated state during the initial rainfall. In addition to saturating the slope surface, the continuous infiltration of rainfall increases the overall water content within the slope, leading to a decrease in matrix suction, i.e., the adsorption of rainwater is reduced, and the rainwater flow is more fluid, which accelerates the expansion of the upper transient saturated zone until the seepage field reaches equilibrium. Thus, the rainfall infiltration under the wetting–drying cycles makes the slope surface gradually saturated through two factors together. On the one hand, the rainfall causes the slope surface to enter the saturated state. On the other hand, the overall increase in the water content in the slope body will also cause the infiltration line to move downward rapidly.
In addition, comparing the distribution of the pore water pressure at the bottom of the lowest local slope and other locations, it can be seen that the pore water pressure at the bottom of the slope is affected by rainfall under different cycle times in a larger area than other areas, and it increases continually until it merges with the water table line, which shows that the rainfall intensity is greater than the saturated infiltration coefficient, leading to rainfall collecting not only along the bottom of the slope but also along the surface of the slope, forming runoff. It is shown that the rainfall intensity is greater than the saturation infiltration coefficient, which causes the rainwater not only to gather at the bottom of the slope along the surface layer but also to flow along the surface of the ground to the bottom of the slope.

4.2. Slope Infiltration Patterns

To better illustrate the distribution of and variation in pore water pressure within the slope body, the central step of the Bang Nau dump was chosen to set a probe line with a fixed vertical direction line segment, in order to reveal the relationship between the pore pressure and depth (Figure 4).

As can be seen from Figure 4, with the increase in the number of wetting–drying cycles, the slope’s pore water pressure increases with the increase in the number of wetting–drying cycles, at the surface of the single-step slope, which is the same as the overall infiltration pattern of the slope in Section 4.1. The water level of the groundwater at this location is almost unchanged with the rainfall cycle, which is located at a depth of about 32.1 m below ground. Through the slope saturation line under different wetting–drying cycles, it can be seen that the infiltration line decreases with the number of wetting–drying cycles. The depth of the step saturation line under different wetting–drying cycles was 3.2 m, 4.1 m, 4.7 m, 5.8 m, and 7.2 m.
4.9 m, 5.6 m and 6.2 m. In the early stage of rainfall infiltration, due to the dryness of the soil body of the drainage field, which resulted in a large gradient of matrix suction, the saturation line moved down faster, but, with the wetting–drying cycles, the rate of descent was reduced. It can be seen that although the infiltration line becomes lower and lower with the rainfall cycle, the rate of decrease in the infiltration line becomes slower and slower. This is because, as the rainfall cycle progresses, the infiltration coefficient of the transient saturated zone out of the surface changes after each rainfall event, and the infiltration location changes in the time taken during subsequent rainfall. Due to the first few cycles, the saturated permeability coefficient of the transient saturated zone will increase; in the next rainfall event, infiltration into the same depth takes less time, i.e., it will leave more time to infiltrate deeper, causing the transient saturated zone range to increase. The infiltration line decreases, but, due to the saturated permeability coefficient in the first two cycles, the saturated permeability coefficient grows faster, so the infiltration line of the first two rainfall cycles decreases faster. The saturated permeability coefficient does not change significantly after two to four rainfall cycles, so the infiltration line decreases more slowly in the third to fifth rainfall events. The permeability coefficient of the rock mass after the fifth rainfall event is \(9.1 \times 10^{-8}\), which is reduced compared to the value of \(9.8 \times 10^{-8}\) for the fourth, and rainfall infiltration is more difficult compared to the previous rainfall. In the subsequent wetting–drying cycles, the saturated permeability coefficient of the rock mass will be further reduced, and the slope infiltration line will not be able to reach the infiltration line in the fifth rainfall event.

![Image](image_url)

**Figure 4.** Slope pore water pressure distribution of slope detection line under wetting–drying cycles.

From the intersection of the pore water pressure–depth curve and the curve without rainfall, after different rainfall cycles, it can be seen that the range of the rainfall-affected zone is always larger than the range of the transient saturated zone after each rainfall event. Moreover, the range of the affected zone continues to increase with the rainfall cycles, and the different times of the wetting–drying cycles are 8.4 m, 9.5 m, 11.3 m, 12.6 m and 14.3 m respectively. Meanwhile, the negative pore water pressure within the affected zone becomes smaller, being \(-2.5\) m, \(-2.6\) m and 14.3 m, respectively. The negative pore water pressure in the influence area also becomes smaller, at \(-64.2\) kPa, \(-63.2\) kPa, \(-61.8\) kPa, \(-60.5\) kPa and \(-59.1\) kPa, respectively, and the matrix suction force becomes larger.

4.3. Displacement Analysis

By analyzing the slope displacements under different wetting–drying cycles, the landslide trend and extent of the slope can be derived, and the slope displacements after different rainfall cycles are shown in Figure 5. In Figure 5, the red area represents the maximum value of slope displacement and the blue area represents the minimum value.
4.3. Displacement Analysis

By analyzing the slope displacements under different wetting–drying cycles, the slope displacement under different numbers of wetting–drying cycles can be divided into three stages. The first stage is when there is no rainfall, and the maximum value of slope surface displacement is located in the third to fifth steps. The range of internal slope displacement distribution is also large, but the peak displacement is low, at only 12 mm, and the risk of a landslide is low. As the rainfall proceeds, according to the pore water pressure distribution in the previous section, it is known that the slope surface will be infiltrated under the high matrix suction gradient, the infiltration of rainfall will saturate part of the rock body inside the slope, and the effective stress of the rock body will decrease with the buoyancy of the infiltrated rainwater. Then, the slope displacement enters the second stage. The second stage includes 1–3 wetting–drying cycles, and the slope displacement in this stage has a significant increase compared with the previous stage’s displacement; the displacement peak is also shifted from the interior of the slope body to the single-step slope. However, the range of slope displacement is reduced with the wetting–drying cycles, and the slope changes from overall displacement to shallow surface displacement. In the third stage, there are four to five wetting–drying cycles. At this time, the deformation range of the slope is completely concentrated in the single-step slope, the peak displacement of the slope is the largest, and shallow landslides are likely to occur under multiple wetting–drying cycles.

![Figure 5. Slope displacement under wetting-drying cycles.](image-url)

(a) Slope displacement under 0 wetting–drying cycle. (b) Slope displacement under 1 wetting–drying cycle. (c) Slope displacement under 2 wetting–drying cycles. (d) Slope displacement under 3 wetting–drying cycles. (e) Slope displacement under 4 wetting–drying cycles. (f) Slope displacement under 5 wetting–drying cycles.
4.4. Plastic Zone Impact

The plastic zone can reflect the damage form and damage range in the slope body. The distribution of the plastic zone of the slope under different rainfall cycles is shown in Figure 6.

As can be seen from Figure 6, the plastic zone of the slope shows mainly shear damage and only a small amount of tensile damage at the surface. The change in water storage in the slope rock body has a significant effect on the plastic zone of the slope rock body. In the process of the wetting–drying cycles, the plastic damage zone is gradually divided into two parts. One part is the plastic damage zone of the slope above the water table line, and this part of the shear damage zone is the main reason for the decrease in slope stability. The other part is the plastic damage zone below the water table line, where the damage zone has almost no effect on the slope stability. Since the plastic damage zone above the water table line has the greatest influence on slope stability, only the plastic zone within
this range is analyzed here. When there is no rainfall, the shear damage zone in the slope body has a large distribution range, and the sheared area is circular. At the beginning of rainfall, the slope rock body changes from the original state of the plastic zone to the state of tensile damage, but as the infiltration line decreases with the number of wetting–drying cycles, the tensile damage zone on the surface of the terrace then disappears. With the wetting–drying cycles, the range of shear damage zones in the body of the slope gradually decreases. Until the fourth rainfall cycle, the range of the plastic zone’s basic change is not obvious; it is manifested in the surface of the shallow steps of the shear damage, which is mainly due to several wetting–drying cycles occurring under the surface of the rock body, caused by the reduction in the physical and mechanical properties.

4.5. Effect of Wetting–Drying Cycles on Slope Stability

The judgment of the location and shape of the landslide on the slope is an important method to analyze the stability of the slope, and the reasonable determination of the location and shape of the sliding surface is an important issue in carrying out the stability analysis of the slope. Geotechnical body damage occurs because the shear stress on a certain side reaches the shear strength of the geotechnical body, so it can be analyzed by analyzing the distribution law of the maximum shear strain of the slope to respond to the potential damage area of the slope damage. The distribution of the maximum shear strain increment of the slope under different numbers of rainfall cycles is shown in Figure 7. In Figure 7, the red area represents the maximum value of the slope’s maximum shear strain increment and the blue area represents the minimum value.

![Figure 7](image-url)

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**Figure 7.** Slope maximum shear strain increment under wetting–drying cycles. (a) Slope maximum shear strain increment under 0 wetting–drying cycle. (b) Slope maximum shear strain increment under 1 wetting–drying cycle. (c) Slope maximum shear strain increment under 2 wetting–drying cycles. (d) Slope maximum shear strain increment under 3 wetting–drying cycles. (e) Slope maximum shear strain increment under 4 wetting–drying cycles. (f) Slope maximum shear strain increment under 5 wetting–drying cycles.

It can be seen that the distribution range of the maximum shear strain increment of the slope before and after the wetting–drying cycles changed significantly. When there was no rainfall, the distribution range of the maximum shear strain increment of the slope was
larger, showing a circular landslide pattern. In the first wetting–drying cycle, the peak in the maximum shear strain increment of the slope was located on the surface of the slope step, but it was still partially distributed within the slope. When the wetting–drying cycles were further carried out, with the weakening of the physical and mechanical strength of the rock body and the combined effect of water, the distribution range of the maximum shear strain increment of the slope was no longer changed, and all of them were located on the surface of the slope, reflecting the damage pattern of single-bench collapse.

The slope factor of safety can most directly reflect the stability of the slope, and the slope factor of safety under different numbers of wetting–drying cycles is shown in Table 3.

Table 3. Waste dump slope factor of safety at different numbers of wetting–drying cycles.

<table>
<thead>
<tr>
<th>Number of Cycles</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Factor of Safety</td>
<td>1.721</td>
<td>1.476</td>
<td>1.213</td>
<td>1.107</td>
<td>1.083</td>
<td>1.055</td>
</tr>
<tr>
<td>Discount Rate</td>
<td>0%</td>
<td>14%</td>
<td>18%</td>
<td>9%</td>
<td>2%</td>
<td>3%</td>
</tr>
</tbody>
</table>

Comparing the slope factor of safety before and after the wetting–drying cycles, it can be seen that it decreases with the wetting–drying cycles. Compared with the non-rainfall condition, the slope factor of safety decreases by about 14 percent in the first wetting–drying cycle, which is mainly caused by two factors: rainfall infiltration and the wetting–drying cycles. The first is the effect of rainfall; the geotechnical body of the slope will reduce the matrix suction under rainfall infiltration, which will reduce the shear strength of the geotechnical body. This will be manifested as a reduction in the resistance to slip force of the slope under the influence of gravity and other factors. The slip force decreases. On the other hand, the infiltration of rainwater will also increase the bulk weight of the geotechnical body, which will increase the downward force of the slope and easily cause landslides. In the process of wetting–drying cycles, the physical and mechanical parameters of the shallow rock mass subjected to wetting–drying cycles will be reduced, and the slope resistance will be reduced, thus decreasing the slope factor of safety. The slope factor of safety decreases with the number of wetting–drying cycles, and the rate of decrease decreases with the increase in the number of wetting–drying cycles. The largest decrease was observed in the second wetting–drying cycle, where it decreased by about 14 percent, which was due to the change in the slope from an overall slip to a localized collapse in a single step, manifested as a shallow landslide on the surface of the slope. In the subsequent wetting–drying cycles, the rate of decrease in the slope factor of safety decreased gradually. This is mainly due to the fact that both the rate of decrease in rock mass cohesion and the depth of the infiltration line show a decreasing pattern as the wetting–drying cycles progress. It can be seen that the slope of the Bang Nau dump is still in a stable state under the condition of many rainfall events in the area, but the slope has a certain risk of surface shallow landslide damage after many wetting–drying cycles. In the subsequent mining and drainage process, in order to reduce the impact of wetting–drying cycles on the dump, the material with a smaller block size and permeability coefficient should be discharged to the surface of the slope, and the top of the slope rock and soil should be compacted. It is also necessary to strengthen the inspection and slope monitoring in the rainy season, and if abnormal slope conditions are detected, measures should be taken to stop the mining activities and redesign the slope.

5. Conclusions

In this study, the slope stability of an open-pit mine discharge site under the influence of wetting–drying cycles in the rainy season in the Cao Son open-pit mine, in the Cam Pha area of Vietnam, was investigated. Experiments on the physical properties of the rock body under different numbers of wetting–drying cycles were carried out, the flow–solid coupling secondary development process and the numerical simulation scheme of wetting–drying cycles were established, numerical analyses were carried out, and some
meaningful conclusions were obtained. The results show that the cohesion of the slope rock body slowly decreases with the number of wetting–drying cycles, the angle of friction changes less, and the permeability coefficient increases, stabilizes and finally decreases with the number of wetting–drying cycles. With the wetting–drying cycles, the maximum positive pore water pressure on the slope surface and the maximum negative pore water pressure in the slope body become larger and larger. The slope showed a transient saturated zone, and the range of the unsaturated zone decreased with the increase in the number of wetting–drying cycles. The saturation line shifted downward faster in the pre-infiltration period due to the dryness of the soil body of the drainage field, and it then decreased with the wetting–drying cycles. After each rainfall event, the range of the rainfall impact area was always larger than the range of the transient saturated area, and with the rainfall cycle, the range of the impact area became larger. The peak slope displacement increased with the number of wetting–drying cycles, and the range of slope displacement and maximum shear strain increment decreased with the number of wetting–drying cycles. This effect was finally focused on the single-step slopes, and the landslide pattern of the slopes reflected a shallow landslide. The slope stability of the Bang Nau dump slope decreased by about 39 percent under the condition of multiple rainfall events in the area with five wetting–drying cycles, and the landslide pattern also changed from a monolithic landslide to a single-stage shallow landslide. Although still in a stable state, the slope has a certain risk of surface shallow landslide damage after many wetting–drying cycles. In order to reduce the impact of wetting–drying cycles on the dump, the material with a smaller block size and permeability coefficient should be discharged to the surface of the slope, and the top of the slope rock and soil should be compacted. It is necessary to strengthen the inspection and slope monitoring during the rainy season, aiming to stop mining activities and redesign the slope if abnormal slope conditions are found. Due to the limited research topic and the space limitations in this paper, more wetting–drying cycle experiments and numerical analyses are required in in-depth research. Moreover, the acidity and alkalinity of rainwater, the temperature and other factors involved in the wetting–drying cycles have not been taken into account, so these factors will be further studied in the future.

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