Stability analysis of an unsaturated pond ash slope subjected to rainfall

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Abstract. In the present study, stability analysis of an unsaturated homogenous pond ash slope subjected to rainfall using the limit equilibrium method based on Bishop and Morgenstern-Price methods under steady-state seepage and transient seepage conditions was carried out. Seepage and stability analyses were carried out using SEEP/W and SLOPE/W models, respectively. The factor of safety (FoS) in the case of the unsaturated pond ash slope was observed to be higher than the saturated slope. The effect of slope geometry, rainfall intensity, anisotropy in permeability, and provision of drains on slope stability were investigated. It is observed that with an increase in rainfall infiltration, there was a tendency of surficial failure when the rate of infiltration is higher than the saturated permeability in the unsaturated pond ash slope. The study assumes importance related to the stability of slopes constructed with coal ash in the context of ever-growing requirements of electricity in the country, slope failures due to extreme weather events associated with climate change, and the requirement of sustainable alternatives, theories, and technologies to tackle the coal ash waste produced.

Keywords: pond ash, rainfall-induced infiltration, unsaturated property functions, slope stability.

1. Introduction

The growing power requirements in developing countries like India have pushed towards consuming natural resources like coal to generate electricity. Despite the measures taken to change the power generation scenario in the country, coal combustion is still a major source of energy production in the country [1]. Along with the depletion of natural sources and increasing global warming, coal as a combustion fuel poses another challenge. The leftover residue after coal combustion, which is commonly known as coal ash, is a nuisance material that would pollute the air, water, and ground if left unchecked. Hence, ash ponds are created to dispose of the residue in line with the design philosophy of tailing dams. However, the ash content in the Indian coal is very high, which is around 30% to 40% [2]. From 2010 to 2020, a total of 1670 million tons of coal ash is still left unused as legacy ash [3]. Also, the land allocated for every 1 MW of power generation is approximately 1 hectare, implying that almost 4 lakh hectares of unused land are lying for waste disposal. In such a scenario, the effective utilization of coal ash becomes prominent. In 2019-20, more than 12.9 million tons of ash were supplied to various Road and Highway construction projects of National Highway Administration of India (NHAI)/State Governments, and as in 2020-21, 15 National Thermal Power Corporation (NTPC) stations are supplying ash to various road projects. In 2020-2021 the ash utilization was expected to cross 20 million tons [4].

The sustainable utilization of ash in various infrastructure projects supersedes a layout where the topsoil is replaced by ash infills, embankments, and retaining walls. The response of such an embankment created with ash to climatic variations becomes vital as in recent years, there has been an increase in the extreme precipitation events in India [5], [6], and around the world due to global warming and climate change. There is an extensive literature available on rainfall-induced slope failures [7-13]. Cho and Lee [7] have conducted a numerical analysis of an unsaturated slope subjected to rainfall infiltration and concluded that the low hydraulic conductivity could shift the failure slip towards the slope surface due to impeded flow. Ng and Shi [8] have investigated the effect of rainfall intensity and duration on the slope stability and observed that the reduction in the magnitude of the Factor of safety (FoS) depended on the rate of precipitation, location of the
groundwater table, duration of rainfall, and permeability of the soil. Rahardjo et al. [9] have conducted a parametric analysis on a homogenous slope and concluded that antecedent rainfalls affect low permeability soils, and the minimum FoS need not necessarily be produced at the saturated coefficient of permeability ($k_s$). They have also concluded that soil properties and rainfall infiltration play a major role in the instabilities of rainfall infiltrated slope failures. Still, very few rainfall-induced failure studies have been carried out specifically on slopes where pond ash has been considered the geotechnical material. Hence, the present study focussed on the various factors that influence the performance of an unsaturated pond ash slope subjected to rainfall.

The analysis of rainfall-induced slope failure was extended to a case of a simple homogenous unsaturated pond ash slope in the present study by performing numerical parametric analysis using SEEP/W [14], SLOPE/W [15]. The variation of height and slope angle on the saturated and unsaturated slope stability, the effect of groundwater table on the FoS, the impact of rainfall via transient seepage analysis, and the influence of the limit equilibrium method and density of the material chosen to perform the stability analysis on the FoS were investigated.

2. Materials and Methodology

The materials used and their properties in the present study were adopted from the literature [16-17]. Initially, the model was validated using the properties of the materials adopted from Rahardjo et al. [9]. The basic geotechnical properties and soil-water characteristic curve (SWCC) [17] of pond ash compacted to the dense and loose condition were used to model the homogenous pond ash slope and analyzed separately. The fitted parameters to the Fredlund-Xing model [17], as given in equation (1), were obtained.

$$\theta_w = C_\psi \frac{\theta_s}{\left[ \ln\left( e + \left( \frac{\Psi}{\theta_s} \right)^n \right) \right]^m}$$

Where, $\theta_w$ is the volumetric water corresponding to matric suction $\Psi$, $\theta_s$ is the saturated volumetric water content, $\Psi$ is the matric suction, $a$, $n$, and $m$ are the curve fitting parameters, and $C_\psi$ is the correction factor.

A summary of material properties considered in the present study are provided in Table-1. Initially, a steady-state seepage analysis using SEEP/W was conducted on the saturated pond ash slope to include the effect of height and slope angle on the stability for a slope height of 5 m, 10 m, 15 m, and slope angle of 1V:2H. The slope height of 5 m and slope angle of 26.7° was used as a reference, and the computed FoS values at varying height and slope angle were reported.

| Material Properties | Coarse Soil | Dense Pond Ash | Loose Pond Ash |
|---------------------|-------------|----------------|----------------|
| Unit weight (kN/m³)  | 20          | 15             | 10.5           |
| Saturated Hydraulic Conductivity ($\times 10^{-6}$ m/s) | 100 | 0.91 | 2.5 |
| The angle of internal friction (deg.) | 26 | 30 | 20 |
| $a$ (kPa)            | 10          | 50             | 23             |
| $n$                  | 1           | 1.63           | 1.25           |
| $m$                  | 1           | 0.96           | 0.80           |
| $\theta_s$          | 0.45        | 0.48           | 0.51           |
Once the pore water pressures were established, the results were carried forward into SLOPE/W [15], and slope stability analysis was performed using limit equilibrium methods as specified by Bishop and Morgenstern-Price, which have been the popular methods to evaluate the FoS. To consider the unsaturated flow and effect of angle of internal friction due to matric suction ($\phi^*$), first SWCC parameters fitted to Fredlund-Xing model [18] as given in [17] were incorporated to represent the suction range of SWCC. SWCC can be very useful to derive other Unsaturated soil property functions, hydraulic conductivity, and $\phi^*$ [19]. The same concept was adopted, and the hydraulic conductivity function was derived by specifying saturated hydraulic conductivity and Fredlund-Xing parameters using the Fredlund-Xing-Huang model [20] as given in equation (2).

$$k_w = k_s \frac{\sum_{i=j}^{N} \theta'(e_i) - \theta'(e_j) \phi'(e_i)}{\sum_{i=j}^{N} \theta'(e_i) - \theta'(e_j) \phi'(e_j)}$$

(2)

Where $k_w$ is the hydraulic conductivity corresponding to the corresponding suction (m/s), $k_s$ is the measured saturated hydraulic conductivity (m/s), $\theta_s$ is the saturated volumetric water content, $e$ is the natural number, $y$ is a dummy variable of integration, $i$ is the interval between $j$ to $N$, $j$ and $N$ are the least and maximum negative pore-water pressures to be decided by the final function respectively, $\Psi$ is the suction at the $j$th interval, and $\theta'$ is the derivation of equation (1).

The present study is limited to the study of homogenous ash slope wherein the air pressure is considered atmospheric. Hence, the change in matric suction can be easily related to a change in negative pore water pressure. SEEP/W was used to conduct a seepage analysis of the slope with both saturated and unsaturated flow parameters. In the case of seepage analysis, the maximum negative pore water pressure was limited to 80 kPa [21] to avoid unrealistic field scenarios with higher suction values. The applied boundary conditions were constant throughout the analysis and are shown in Figure 1. A no-flow boundary condition was simulated on either side of the slope above the water table and at the bottom of the slope. Consequently, a transient seepage analysis was conducted by taking the rainfall as a step function of water flux and applied as a surface flux boundary condition on the slope faces. The position of the initial water table was considered as described in Rahardjo et al. [9].

Once the results were obtained from the transient seepage analysis, they were used as input parameters in SLOPE/W. The material properties were taken from a sensitivity analysis on the homogenous pond ash slope by varying internal friction angles, ignoring the effect of cohesion. The Mohr-Coulomb model was used with unsaturated parameters calculated [22] as given in equation (3), and the SWCC of the pond ash was given as an input parameter. The FoS was calculated using the Morgenstern-Price Method and Bishop’s Method.

$$s = c' + (\sigma_n - u_a) tan \phi' + (u_a - u_w) \left[ \frac{\theta_w - \theta_r}{\theta_s - \theta_r} \right] tan \phi'$$

(3)

Where $s$ is the shear strength of the soil, $c'$ is effective cohesion, $\phi'$ is the angle of internal friction, $(\sigma_n - u_a)$ is net normal stress, $(u_a - u_w)$ is matric suction, $\theta_w$ is the volumetric water corresponding to matric suction $\Psi$, $\theta_s$ is the saturated volumetric water content, and $\theta_r$ is the residual volumetric water content.

The effect of infiltration rate on FoS was studied by giving infiltration rates as multiples of the saturated coefficient of permeability. The density effect on the strength was found by analyzing loose pond ash material with different saturated hydraulic conductivity and different internal friction angles. However, the effect of vegetation on the surface layer was ignored to get a conservative estimate of FoS. At last, the effect of providing horizontal drains on the stability of the slope was
also studied and reported. The effect of variation of the $\phi^b$ on the FoS of pond ash slope was studied by varying the value of $\phi^b$ from 5° to 15°.

3. Validation of the Numerical Model
A 10 m high homogenous embankment was considered, and the geometry, material properties, and boundary conditions [9] were recreated for validation. The coarse material [9], which has the properties given in Table-1, was subjected to various rainfall intensities for one day. The geometry and boundary conditions of the model considered for validation can be seen in Figure-1. The initial groundwater table was selected at a depth of 5 m from the ground level [9]. Equal total heads were applied to the regions falling under the groundwater table. All the other faces had no-flow boundary conditions where the water could not enter or exit the face.

![Figure 1. Schematic diagram of the pond ash slope model and applied boundary conditions.](image)

Transient seepage analysis was performed by subjecting the slope to one-day rainfall of different intensities (9 mm/hour, 80 mm/hour, and 360 mm/hour) and recorded measurements for a total of ten days, following which slope stability analysis using Bishop’s method was performed. FoS vs. elapsed time graphs were plotted in each case, and the minimum FoS at the end of one day period was obtained and compared with the minimum FoS in [9]. The values obtained are given in Table-2. As the computed FoS values after one-day rainfall was found to be approximately equal in comparison, the model was thus considered validated. The simulation was extended further to the study of unsaturated pond ash slope.

| FoS$_{min}$ | 9 mm/h | 80 mm/h | 360 mm/h |
|------------|--------|---------|----------|
| Rahardjo et al. [9] | 1.153  | 1.479   | 2.372    |
| Present Study   | 1.161  | 1.408   | 2.444    |

4. Results and Discussion
4.1. Seepage and Stability Analysis on Saturated Pond Ash Slope
Initially, a conventional steady-state seepage analysis followed by slope stability, including sensitivity analysis with varying shear parameters, i.e., angle of internal friction, was performed by
assuming that the pond ash material was completely saturated. The resulting minimum FoS values obtained are tabulated in Table-3 at a constant density of 15 kN/m³.

**Table 3.** The FoS of a densely saturated pond ash slope for a rainfall infiltration of $k_s$ mm/hour for a density of 15 kN/m³ and $\varphi' = 30^\circ$

| Height of Slope | Steady State Seepage | Transient Seepage |
|-----------------|----------------------|-------------------|
|                 | Bishop | MP | Bishop | MP |
| 5 m             | 0.48   | 0.48 | 1.16   | 1.16 |
| 10 m            | 0.46   | 0.47 | 1.16   | 1.16 |
| 15 m            | 0.45   | 0.46 | 1.16   | 1.16 |

The FoS values for steady-state seepage were consistently low compared with transient analysis because of the inert assumption of steady seepage that the rainfall occurs indefinitely before the soil comes to equilibrium. The effect of the angle of internal friction on the FoS is observed to be more predominant than the effect of unit weight for the same height and boundary conditions. As the same boundary conditions and similar water tables were maintained throughout the analysis, the effect of height on the stability of the saturated slope was minimal. It can also be observed that there is not much variation in the FoS based on the analysis method. Also, a transient seepage analysis followed by conducting a slope stability analysis by applying the largest recorded one-day rainfall in India [23] of 80 mm/hour on a 5 m high, 1V: 2H slope using Bishop and Morgenstern-Price methods revealed that there was no difference in the computed FoS values. It can be seen in Figure 2. Hence, only Bishop's limit equilibrium method was chosen to calculate the FoS further into the study.

![Figure 2. FoS versus elapsed time for a rainfall intensity of 80 mm/hour was considered in the study.](image)

The analysis was extended for a transient seepage analysis to recreate the field scenario by considering saturated-unsaturated parameters, where the rainfall has a definite duration and subsequent slope stability using Bishop's method. Once the analysis was carried out on a reference slope of 5 m height and a slope angle of 1V: 2H, the study was extended to include variations in slope geometry, rainfall, anisotropy in permeability, variations in $\varphi^b$, and effect of providing drains.

4.2. Seepage and Stability Analysis on Unsaturated Pond Ash Slope

The unsaturated slope, as described in Section 2 by taking the unsaturated material properties, was considered for the study. Suction profiles and FoS vs. Time plots were analyzed for varying geometry of slopes, shear parameter, rate of infiltration, anisotropy in hydraulic conductivity, and provision of
drains. FoS variation with $\varphi^b$ was studied, and the results were reported. The complete details of the analysis are presented in the subsequent sections.

4.2.1. Effect of Geometry and $\varphi'$ on the FoS. Initially, the variation in FoS for 3 m, 5 m, 10 m slope was studied to consider the effect of slope height on stability. Similarly, FoS at 1V: 1.6 H, 1V: 2H, and 1V: 3H were also analyzed. Finally, a sensitivity analysis was performed by assuming a sensitivity offset function for $\varphi'$ and varied from 25° to 35° and values were reported for the worst-case scenario at $\varphi'=25°$. The minimum Factor of safety ($F_{s_{\text{min}}}$) values obtained by steady-state seepage on the unsaturated slope were almost like that of steady saturated seepage conditions and hence were ignored in the analysis. The suction profile results from the present study suggest that with an increase in height and decrease in slope angle, the suction reduction at a section near the face of the slope is higher than at a section at some distance from the slope. FoS vs. elapsed time plotted for varying heights, and slope angles are shown in Figure 4 (a), (c). The initial FoS was higher in the case of a flatter and shorter slope as expected. However, the rate of decrease of FoS after the rainfall event was also higher in the case of the shorter slope, which might be due to the availability of immediate draining response of the shorter slope to the rainfall. In the case of varying slope angles, the steeper slope had the minimum FoS and rapid response. The results of the sensitivity analyses are presented in Figure 4 (b) (d) on different heights and slope angles, respectively. The effect of variation of $\varphi'$ was more sensitive to variation in slope angle rather than the height of the slope. Hence while designing a slope, careful consideration must be given in flattening a slope.

![Figure 3](image-url)

Figure 3. (a) FoS versus elapsed time for a reference slope angle of 26°, (b) Minimum FoS versus height of slope for varying $\varphi'$, (c) FoS versus elapsed time for a reference slope height of 6 m, (d) Minimum FoS versus slope angle for varying $\varphi'$. 
4.2.2. Effect of rate of infiltration and density on slope stability. The dense pond ash slope with a reference height of 5 m and reference slope angle of 1V: 2H was reconstructed. All the boundary conditions except surface flux boundary conditions remained the same. The effect of rainfall intensity and, in turn, the infiltration rate on the stability of slope was studied by applying rainfall fluxes of k, 2k, 4k, and 80 mm/hour on the surface of the slope and the results are plotted in Figure 5. Initially, with the increasing rainfall intensity, there is a steep decrease in FoS, after which a threshold limit is reached. Beyond this point, the variation of FoS becomes almost constant. This can be explained by having a closer look at Figure 5 (a) which is the plot between matric suction at the toe of the 5 m high and 26° slope and elapsed time for various rainfall intensities. With increasing rainfall intensity, there is a considerable reduction in matric suction. Still, beyond a certain limit, the matric suction vanishes completely, and hence the FoS reaches a constant value, as shown in Figure 5 (b). The reduction rate with rainfall intensity is rapid till a certain point beyond which it reaches saturation value.

![Figure 4.](image)  
(a) Matric suction versus elapsed time at the toe of slope for various rainfall intensities,  
(b) Minimum FoS vs. rainfall intensity with varying \( \phi' \).

To understand the effect of density on stability, the present study considered a simple case of loose pond ash slope described in section 2. The analyzed FoS with respect to time values is presented in Figure 5. The FoS reached a critical value even with a rainfall intensity of k, mm/hour compared with a dense pond ash slope. With the increasing density of the pond ash, close packing of the particles helps maintain a good bond with water, increasing the resistance to drain and improving suction and strength characteristics. For a sensitivity analysis conducted by varying material shear parameter \( \phi' \) from 12°-20°, the worst-case was encountered at 12° and plotted in Figure 5. With decreased density achieved in the field, there is a chance of increasing the reduction rate of FoS with rainfall infiltration into the slope.

![Figure 5.](image)  
FoS versus elapsed time for a loose pond ash slope of 5 m height and a 26° slope angle.
4.2.3. Effect of anisotropy in permeability and provision of drainage conditions. The influence of variation in hydraulic conductivity ratio (HCR) on FoS was investigated and reported, as shown in Figure 6. With increasing HCR, the shape of the FoS vs. Elapsed time changed. The minimum FoS encountered in the case of isotropic permeability was at the end of 1-day rainfall. However, as the HCR increased, the draining capability of the slope in the horizontal direction increased, and the F_s,min after one-day rainfall shifted up. Still, the FoS continued to decrease even after the end of rainfall. The F_s,min decreased till a certain value of HCR, after which it slightly increased with an increase in HCR, which can be observed from Figure 6 (b). However, a significant increase in FoS was not observed.

Figure 6. (a) Effect of anisotropy in permeability on FoS of the slope, (b) Plot between minimum Factor of safety and hydraulic conductivity ratio.

Horizontal drains were provided at the bottom of the 5 m high, 26° slope, and subsequent analysis was carried out. The results thus obtained are plotted in Figure 7. Clearly, with the provision of drains, more water was available to be readily drained, which helped maintain the field suction conditions of the slope. Hence, the FoS increased instead of reducing with time. The provision of proper drainage can enhance the unsaturated strength of the pond ash slope.

Figure 7. Effect of providing drains on Factor of Safety.

4.2.4 Effect of $\phi^b$ on the Slope stability. The analysis was ended by studying the effect of the angle of internal friction due to matric suction on slope stability. For this purpose, the $\phi^b$ values considered were 5°, 10°, and 15°. With increased infiltration, the suction slowly diminished and resulted in a surficial failure, as observed by [9]. The minimum safety factor encountered after the one-day rainfall period was plotted against $\phi^b$ values in Figure 8. The influence of $\phi^b$ on the minimum FoS value dwindles slightly with increasing rainfall intensity. As the air entry value is between 20 kPa-200 kPa,
the maximum $\varphi_b$ that can be considered is limited to $15^\circ$ [11]. For the rainfall intensity greater than 4 k, mm/hour, the safety factor is less than the safe value even for a $\varphi_b$ value of $15^\circ$. Hence, the influence of matric suction after a certain threshold value of rainfall intensity on strength and stability becomes less important. However, unsaturated transient seepage analysis is required to arrive at the threshold value and better understand field conditions.

![Figure 8](image_url)

**Figure 8.** Minimum FoS versus $\varphi_b$ values for different rainfall intensities.

### 5. Conclusions

The present study investigated the factors influencing the stability of a homogenous unsaturated pond ash slope, and the following observations are made:

- The saturated steady-state seepage conditions provide conservative and uneconomical FoS values. They do not represent the field conditions closely compared with Unsaturated Transient seepage conditions, and Bishop and Morgenstern-Price methods have given similar results in finding the FoS values.
- The slope angle’s effect is predominant on the stability of the slope, and the antecedent rainfall conditions might have a significant effect on higher slopes. The higher the $\varphi'$ and denser the ash, the greater the FoS.
- The FoS of pond ash slope decreases rapidly with rainfall intensity until a certain threshold value and remains approximately constant. It was also observed that reduction in field density might lead to changing hydro-mechanical parameters, which might negatively impact the stability of the pond ash slope.
- The anisotropy in permeability generally encountered in the field may be considered, as these changes can skew the results in a completely different path. It was also concluded in the present study that provision for drainage is very important as it can help in maintaining the suction or even, in some cases, increase the resistance of slope against failure.

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