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Stability Analysis of Slope Induced with Coal Ash Dykes

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Abstract. Safe disposal of coal ash slurry is a primary concern of the environment owing to the bulk generation of ash in industries, especially in any developing country. Generally, it is observed that the generated coal ash waste is disposed of into the ash ponds as slurry. Ash dyke breaches may inundate the surrounding area with toxic ash slurry, thus inducing a high environmental hazard. This article presents a study on the slope stability of ash dyke structures for different geometries, which may be constructed of various materials and are subjected to varied seepage conditions. The present analysis compares different dyke erection methodologies, namely the upstream method, centreline method and downstream method. Numerical analysis is performed using Geostudio Slope/w software. The study found that ash dyke safety increases when the dyke structures are designed with adequate drainage. Further, from this study, it can be concluded that the dyke stability not only depends on the geotechnical properties of the ash material used in its construction but also on the design of the dyke, the method of erection and the seepage through the dyke.

Keywords. Ash dyke, slope/w, phreatic line, Bishop method, slope stability

1. Introduction

Combusting coal in industry and power plants produces combustion residues that may not be reused completely. Consequently, to discharge this, a large amount of coal ash residue has to be disposed of as slurry in the wet disposal units. For this purpose, ash ponds are constructed, generally embanked by ash dykes. The reports on fly ash generation at coal/lignite-based thermal power stations and its utilisation show that there has been a significant increase in the generation of fly ash from 1996 to 2021, notably so, having a utilisation rate of about 92.41% in the year 2020-21 [1]. For the safe disposal of ash and management of ash ponds, the stability of ash dykes is a key concern. Ash dykes are containment structures to prevent ash pond slurry from flowing away. Although the proportion of coal ash residue has increased as different properties of ash, have been investigated and its utilisation as a construction material has increased in recent years, a voluminous amount of ash still ends up as a waste product. The low ash utilisation rate of a thermal power plant may also be attributed to other

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factors like proximity and number of units which require ash as construction material, namely cement and brick manufacturing units [2]. Determination of stability of slope is very well highlighted in the past studies [3-8].

Ash slurry contains toxic chemicals and metals, spilling of which can cause massive damage. Due to heavy metals, leachate of ash ponds can easily contaminate the water bodies and soil [9]. There are different methods of increasing the elevation of the dyke structures [10]. Improper compaction can compromise the integrity of dyke, especially in upstream raising method, starter dyke properties are not good for construction, complications during the design of ash dyke because of the absence standard guidelines for design and maintenance of coal ash dyke and due to seismic loading [11]. The underlying physics of dyke failure and suggested limit state equations responsible for different failure modes [12]. The ash dyke raisings may be constructed in different methods. This type of structure is very unstable under earthquake loading because of liquefaction [13]. Nonetheless, the raising is generally constructed by the upstream method where land is limited. The centreline method of incremental raising involves the simultaneous raising of upstream and downstream slopes to optimally dispose of the ash in the dyke. Material is placed on either side of the centre line of the dyke such that the location of the centre line remains the same after the first stage of filling [14]. For the construction of an embankment using ash, one could assume ash as soil for the design purpose, and the principle of soil mechanics can be applied [15].

Unutilised fly ash is disposed of in slurry form in ash ponds only after properly monitoring the amount of toxic metals like mercury, lead, chromium, etc., within permissible disposable limits [16]. The design of recomposite liners which could retain toxic chemicals and heavy metals and prevent the contamination caused by leachate [17]. Few researchers have explained the design of ash bunds and stated the environmental implication of ash disposal and suggested ways to utilise the ash produced and studied the ash settling in the ponds [18]. Applicability of prefabricated vertical drains for consolidating the ash slurry on which the dyke raising rests in the upstream method have also been highlighted in some studies [19].

The inherent limitation of the large time interval between the construction of raising by central line raising method and the service time and suggested peripheral filling of dry pond ash between the main and peripheral dyke to reduce the time of construction and increase the safety of structure. Studies have shown that any embankment performs best when under seismic loading when the berm is provided at half the embankment height [20]. The systematic approach of safe disposal and ash pond management, including the emergency preparedness and response procedure have been discussed and the reclamation technique of abandoned ponds is highlighted in past studies [21]. Essentially the analysis of dyke stability involves multiple parameters such as seepage happening through the dyke, the material used to construct dyke, the slope and dyke geometry, and stages of dyke raising. It may be highlighted that the seepage condition plays a critical role in the stability of the dyke. This phenomenon has been explored later in the findings of the present work.

Stability of the dyke structure are mostly governing by the structural parameter and if it breaches occurs it is mostly because of the lack of construction methodology and inadequate analysis. The geotechnical properties of the material used in constructing the ash dyke, including the proportions of bottom ash and fly ash, are considered in the present study. This study aims to investigate factors which are responsible for ensuring dyke safety and the extent to which they influence the factor of safety (F.O.S.) of the ash dyke. The position of the phreatic line and the seepage conditions and drainage provided through the dyke affect the safety of the ash dyke. The slope gradient of the dyke determines its structural stability and the extent to which the slope can be steepened without compromising safety. The method of dyke raising, including the upstream, centreline and downstream methods, affects the safety of the ash dyke.

2. Methodology

The present analysis involves the study of slope safety of the downstream side of the ash dyke under steady seepage conditions. The ash pond is assumed to be completely filled with hydraulically deposited ash slurry. Ash dykes are containment structures to prevent ash pond slurry from flowing away.

2.1. Design Geometry

The ash pond embankment rests a thick and well-compacted foundation over which a starter dyke is constructed. In the analysis, the starter dyke is kept the same for all models, but the subsequent stages of the dyke (also called raisings) have been varied. The downstream slope of the starter dyke is 2.5H: 1V and the upstream slope is 2H:1V, both crest width and the elevation of 5m. The ash dyke raising constructed over the starter has a slope of 2H: 1V or 3H: 1V, crest width of 3m and height of 5m. Dyke structures have been raised using the three methods discussed earlier for comparison. Moreover, multi-stage raising has also been constructed for inferring the change in the FOS of the downstream slope of raisings compared to the single-staged raising. The three different methods of dyke raisings have been analyzed and compared with each other.

2.2. Seepage Conditions

Slope stability analysis has been carried out in the steady state seepage condition with the pond filled up to its full height. Analysis corresponds to two cases: (i) FOS when the phreatic line is high, which corresponds to inadequate drainage through dyke leading to uncontrolled seepage, and (ii) FOS when the phreatic line is low, which corresponds to adequate drainage through dyke leading to controlled seepage these raising.

A starter dyke is assumed to comprise the foundation of local soil (saturated silty clay). Different types of ash material have been referred to study the impact of material used in ash dyke construction on its stability. One of the ash materials is significantly coarser with large proportions of bottom ash, while the other sample has negligible bottom ash proportions, thus sand content of less than 10%. Ash slurry, which the pipes transport to the wet disposal unit, is disposed of in the ash ponds. The geotechnical properties of hydraulically deposited saturated ash slurry have also been contained in table 1.

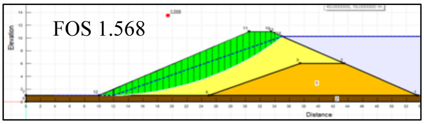

Figure 1. Downstream dyke model without proper drainage, downstream slope 2H: 1V and upstream slope 2H: 1V, using sample A

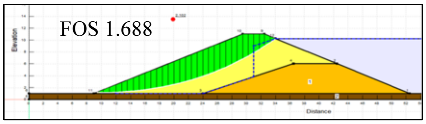

Figure 2. Downstream dyke model with proper drainage, downstream slope 2H: 1V and upstream slope 2H: 1V, using sample A

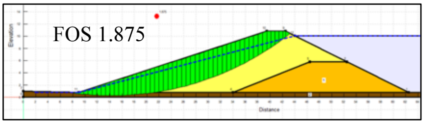

Figure 3. Downstream dyke model without proper drainage, downstream slope 3H: 1V and upstream slope 2H: 1V, using sample A.

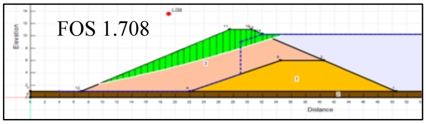

Figure 4. Downstream dyke model with proper drainage, Upstream slope 2H: 1V and Downstream slope 2H: 1V, using sample B.

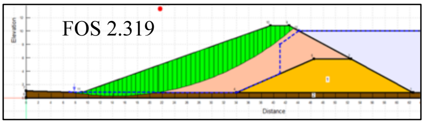

Figure 5. Downstream dyke model with proper drainage, downstream slope 3H: 1V and Upstream slope 2H: 1V, using sample B.

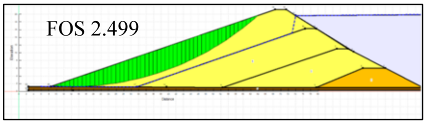

Figure 6. Downstream triple stage dyke model with proper drainage, downstream slope 3H: 1V and upstream slope 2H: 1V, using sample A.

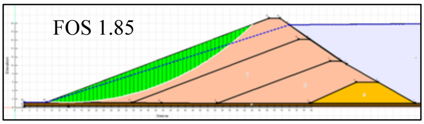

Figure 7. Downstream triple stage dyke model without proper drainage, downstream slope 3H: 1V and upstream slope 2H: 1V, using sample B.

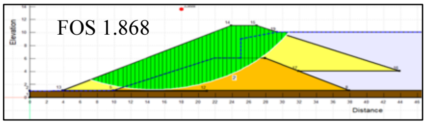

Figure 8. Centreline dyke model with proper drainage, downstream slope 2H: 1V and upstream slope 2H: 1V, using sample A.

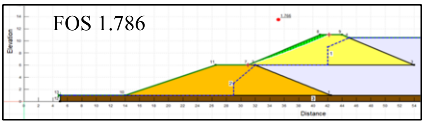

Figure 9. Upstream dyke model with proper drainage, downstream slope 2H: 1V and upstream slope 2H: 1V, using sample A.

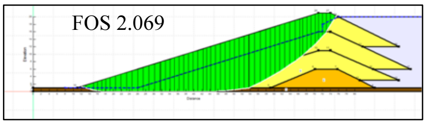

Figure 10. Centreline dyke model with proper drainage, Upstream slope 2H: 1V and Downstream slope 3H: 1V, using sample A.

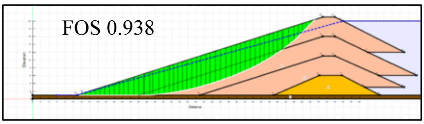

Figure 11. Centreline triple stage dyke model without proper drainage, upstream slope 2H: 1V and Downstream slope 3H: 1V, using sample B.

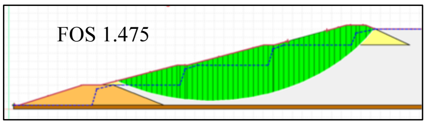

Figure 12. Upstream triple stage dyke model with proper drainage, downstream slope 2H: 1V and upstream slope 3H: 1V, using sample A.

2.3. Material Properties

The details of the material properties are summarized in table 1.

Table 1. Geotechnical properties of materials [22].

Material		Type	Specific Gravity	Unit weight (kN/m³)	Saturated Unit Weight (kN/m³)	Cohesion (C') (kN/m³)	Angle of internal friction(ø') (Degree)
Foundation material		Silty Clay	2.70	18.5	20	14	24.5
Starter dyke		Sandy	2.63	19.5	23	6	30
1st level Dyke	Ash Sample 'A'	S(B&F)*	2.26	16.2	18	0	39
	Ash Sample 'B'	S(F)**	2.22	15.5	21.5	0	30
Slurry ash		Silty sand	2.24	13	19.5	0	28

* Well compacted ash sample having both bottom ash and fly ash
** Well compacted sample without bottom ash
<u>Noteworthy Points</u>:
Specific gravity of the coal ash is considerably lower than that of natural soils which are used in the foundation and the starter dyke.
Effective shear strength parameters (C') and (ø') are based upon direct shear test performed on the saturated samples in both loose and dense states.

3. Result and Discussion

The models were analyzed under varying conditions. It has been observed that slope stability is dependent on several parameters summarized in table 2. Figure 1 shows the downstream dyke model without proper drainage, downstream slope 2H:1V and upstream slope 2H: 1V, using ash sample A. FOS for the critical slip surface is 1.568. The sketch in figure 2 depicts the downstream dyke model with proper drainage, downstream slope 2H: 1V and upstream slope 2H: 1V, using ash sample A. The FOS obtained for the critical slip surface for this case is 1.688. Figure 3 represents the downstream dyke model without proper drainage, having downstream slope 3H: 1V and upstream slope 2H: 1V, using ash sample A. For this model, the derived FOS for the critical slip surface is 1.875. The cross-section of the model shown in figure 4 is for the downstream dyke model with proper drainage, with upstream slope 2H: 1V and downstream slope 2H: 1V, using ash sample B. In this case, the calculated FOS for the critical slip surface is 1.708. Figure 5 shows the downstream dyke model with proper drainage, having a downstream slope of 3H: 1V and an upstream slope of 2H: 1V, using ash sample B. The obtained FOS for the critical slip surface is found to be 2.319.

For the downstream triple-stage dyke model with proper drainage with downstream slope 3H: 1V and upstream slope 2H: 1V using sample A ash, the FOS for the critical slip surface was found to be 2.499, as shown in figure 6. The FOS for the critical slip surface is 1.854 for the downstream triple-stage dyke model without proper drainage using ash sample B having downstream slope 3H: 1V and upstream slope 2H: 1V, as shown in figure 7. The centerline dyke model with proper drainage, upstream slope 2H: 1V and downstream slope 2H: 1V, using sample A ash, is shown in figure 8. The FOS for the critical slip surface for this case is 1.868. The upstream dyke model with proper drainage, downstream slope 2H: 1V and upstream slope 2H: 1V, using sample A, is shown in figure 9. The obtained FOS for the critical slip surface is 1.786. Figure 10 depicts the centerline dyke model with proper drainage, having upstream slope 2H: 1V and downstream slope 3H: 1V, using sample A ash. FOS for the critical slip surface is 2.069. The centerline triple-stage dyke model without proper drainage with upstream slope 2H: 1V and downstream slope 3H: 1V, using sample B ash, is shown in figure 11. The FOS for the critical slip surface is 0.938. Figure 12 shows the upstream triple-stage dyke model with proper drainage, downstream slope 2H: 1V and upstream slope 3H: 1V, using ash sample A. The FOS for the critical slip surface is 1.475. The upstream triple staged dyke model without proper drainage, downstream slope 2H: 1V and upstream slope 3H: 1V, using sample B ash, is shown in figure 13. The value of FOS obtained for the critical slip surface is 0.934.

Table 2. Factor of Safety of different models.

		Sample A				Sample B			
		2H1V		3H1V		2H1V		3H1V	
		HPL	LPL	HPL	LPL	HPL	LPL	HPL	LPL
Single Staged Raising	Downstream	1.568	2.100	1.875	2.876	1.325	1.708	1.482	2.319
	Centreline	1.368	1.868	1.758	2.587	1.249	1.538	1.219	1.943
	Upstream	1.257	1.766	1.614	2.357	1.129	1.477	1.196	1.831
Triple Staged Raising	Downstream	1.168	1.926	1.554	2.499	0.948	1.623	1.039	1.854
	Centreline	1.110	1.562	1.375	2.069	0.765	1.205	0.938	1.734
	Upstream	0.875	1.121	1.048	1.475	0.34	1.067	0.934	1.4

Slope stability is affected by the type of material which is being used for its construction. For the construction of the first stage of the dyke both the materials fly ash and bottom ash are considered, and in other cases, only fly ash is used to construct the dyke. From the obtained results, it can be summarised that when only fly ash is used, the slope stability has decreased compared to when both fly ash and bottom ash. The chimney drain plays a very crucial role in the stability of dyke. The stability of the dyke considerably reduces when the drainage is not controlled, or the chimney drain is not working properly. In the cases when the seepage was controlled, the FOS has been observed to get increased. The FOS is also critically governed by the steepness and the slope of the dyke; in other words, there is a critical relationship between the slope or steepness of the dyke and the FOS. Steeper slopes are found to be less stable, as observed above F.O.S (3:1) > F.O.S (2:1). The downstream dykes are more stable compared to the upstream dykes, all other conditions being the same. The FOS values for the critical slope surface of centerline dykes have been found to lie somewhere between the FOS values of the other two raisings.

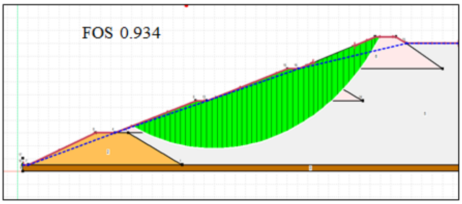

Figure 13. Upstream triple staged dyke model without proper drainage, downstream slope 2H: 1V and upstream slope 3H: 1V, using sample B.

In the present study, it is noticed that compared to 2H:1V, the 3H:1V provides the dyke structure more stability in both the absence and the presence of proper drainage. The factor of safety was increased by 20% to 30%. When sample A was replaced by sample B, it was observed that the FOS of all the raising types decreased by 10-15%. The FOS values remain in the same order in downstream raising with a maximum value of 1.325 and upstream raising with a minimum value of 1.129.

4. Conclusion

The current study presents the slope stability analysis of ash dyke structures of different geometries constructed using various materials and subjected to varied seepage conditions. The safety parameters of the downstream slopes of dykes have thus been investigated to draw the following conclusions:

- Safe operation of ash ponds can only be guaranteed if the dyke structures constructed to embank them are also stable.
- Waste ash may be utilized to construct an ash dyke, but the safety of dyke slope remains the priority. Failure of ash dykes can be prevented if the safety parameters are adequately taken care of while carrying out the analysis.
- It has been found that the dyke stability not only depends on the geotechnical properties of the ash material used in its construction but also on the design of the dyke, the method of raising and the seepage through the dyke while the pond is in operation.
- The safety of dyke can be ensured by controlling seepage using chimney drains, or its steepness may be decreased to increase the FOS. Besides, larger proportions of bottom ash fraction render greater safety than fly ash as construction material. Moreover, downstream dykes and generally the safest, followed by the centerline dykes and upstream dyke raising being the most vulnerable out of the three. If the upstream method has to be adopted, the ash material should have larger proportions of coarse ash, and a proper chimney drain should be ensured.

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References

[1] Central Electricity Authority of India. Report on Fly Ash Generation at Coal/Lignite Based Thermal Power Stations and Its Utilization in the Country for The Year 2020-21. New Delhi, 2021.

[2] Arora S. An Ashen Legacy: India's thermal power ash mismanagement. New Delhi, 2020.

[3] Paswan AP and Shrivastava A. Stability analysis of rainfall-induced landslide. 3rd International Online Conference on Emerging Trends in Multi-Disciplinary Research, 2022.

[4] Paswan AP and Shrivastava A. Numerical modelling of rainfall-induced landslide. International e-Conference on Sustainable Development & Recent Trends in Civil Engineering, 2022.

[5] Paswan AP. and Shrivastava AK. Evaluation of a tilt-based monitoring system for rainfall-induced landslides: Development and physical modeling. Water. 2023; 15(10). doi: 10.3390/w15101862.

[6] Paswan AP. and Shrivastava AK. Modelling of rainfall-induced landslide: a threshold-based approach," Arab. J. Geosci. 2022; 15(8). doi: 10.1007/s12517-022-10024-6.
[7] Roshan P and Pal S. Seismic safety of buildings on indian hill slopes — A review. Recent Advances in Earthquake Engineering Select Proceedings of VCDRR 2021, 2021; pp. 197–209, doi: 10.1007/978-981-16-4617-1.
[8] Roshan P and Pal S. Structural challenges for seismic stability of buildings in hilly areas. Environ. Sci. Pollut. Res. 2022. doi: 10.1007/s11356-022-23263-7.
[9] Ragucci J. Overview of Coal Combustion Residuals (CCR) and TVA Kingston Case Study. University of Florida, 2018.
[10] Shivamanth A, Athani SS, Desai MK and Dodagoudar GR. Stability analysis of dyke using limit equilibrium and finite element methods. Aquatic Procedia. 2015; 4(ICWRCOE-2015): 884–891, doi: 10.1016/j.aqpro.2015.02.111.
[11] Chauhan S. Design and Slope Stability Analysis of a Proposed Ash Pond for Waste to Energy Plant in Shimla. Jaypee University of Information Technology, 2017.
[12] Li J. Probabilistic risk analysis of dyke failure modes using FTA. Saf. Reliab. 2018; 37(2–3): 128–147. doi: 10.1080/09617353.2018.1468656.
[13] Munaga T, Charan PS, Raju MRSK, Yerra L and Kothakota B. Suitability of flyash in raising the embankments. Indian Geotechnical Conference (IGC) 2018, 2018, no. July 2019, pp. 1–5.
[14] Zardari MA. Stability of Tailings Dams - Focus on Numerical Modelling, Licenciate Thesis. Luleå University of Technology, 2011.
[15] Mauriya VK. Management of peripheral filling in centerline method of raising of ash dyke to match the operational requirement of ash disposal. Indian Geotechnical Conference (IGC) 2018, pp. 2–5.
[16] Ghosh P and Goel S. Physical and chemical characterization of pond ash. Int. J. Environ. Res. Dev. 2014; 4(2): 129–134, 2014.
[17] Kommu S and S Asadi. Design of eco-friendly geo-composite liner for fly ash ponds. Int. J. Innov. Technol. Explor. Eng. 2020; 9(3): 3517–3521. doi: 10.35940/ijrte.c8309.018520.
[18] Ghazali M and Kaushal OP. Characteristics of fly ash from thermal power plants and its management along with settling pond design. Int. J. Eng. Res. Sci. 2015; 1(4): 24–32.
[19] Rao GV and Pothal GK. Improvement of pond ash with prefabricated vertical drain. Indian Geotechnical Conference: IGC-2009, 2009, no. May, pp. 852–857.
[20] Khodary SM and Ibrahim KMHI. Effect of adding downstream berms on seismic mitigation of embankments. J. Eng. Sci. 2014; 42(2): 317–324. doi: 10.21608/jesaun.2014.114732.
[21] Naresh DN. Management of Ash Disposal. 2010.
[22] Pant A, Datta M and Gunturi VR. Influence of engineering behaviour of coal ash on design of ash dykes. Indian Geotechnical Conference: IGC-2016, 2016, no. December, 2016, pp. 1–4, doi: 10.1007/978-981-13-0899-4_27.