Preliminary Study of Artificial Slope Facets from Coal Dump Sites

Adrija Raha, Suvashree Das, Mery Biswas, and Soumyajit Mukherjee

Abstract Coal dump sites offer useful perspectives to understand stability of artificial slopes. Such studies require geotechnical research, which can be aided by numerical simulation model-based stability evaluations. Anthropogenic geomorphology can be well studied at the coal dump sites. Four coal dump sites close to Durgapur and Dhanbad (eastern India) have been examined in this study in order to better understand the different aspects of slopes and their instability risk. The studied anthropogenic landforms have clearly demonstrated the different slope segments e.g. free face, convex and concave. The majority of slumping occurs with >50° slopes. Natural vegetation partly stabilised the studied slopes. Improved management of the dump slope will contribute to the accomplishment of the Sustainable Development Goals (SDG), which include safeguarding land life and providing clean water and sanitation.

Keywords Dump-site geomorphology · Slope stability · Geomorphology · Neogeomorphology · Anthropogenic geomorphology

Abbreviations

DEM	Digital Elevation Model
NCL	Northern Coalfields Limited
OCP	Open Cast Project
PAHs	Polycyclic Aromatic Hydrocarbons
TS07	Total Station 07

A. Raha · S. Das · M. Biswas
Department of Geography, Presidency University, Kolkata, West Bengal, India

S. Mukherjee (✉)
Department of Earth Sciences, Indian Institute of Technology Bombay, Mumbai, Maharashtra, India
e-mail: smukherjee@iitb.ac.in

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Highlights

I. Coal dump sites provide ideal place to study anthropogenic landforms
II. The slope of the dump sites are distinctly varied in terms of concavity or convexity
III. Vegetation plays an important role in the slope stability.

1 Introduction

In recent years, there has been a noticeable increase in environmental awareness amongst the public, driven by growing recognition of human's substantial impact on natural ecosystems (Dávid, 2008). Anthropogenic geomorphology/neogeomorphology is a relatively new field within the Quaternary science that has gained much focus in the last two decades or so (Lóczy & Süto, 2011). The subject examines surface alterations resulting from human activities, predicts the repercussions of disrupting natural equilibria, and proposes strategies to mitigate adverse impacts.

Mine dump is one of the human-induced landforms (review in Mohanty et al., 2024). The morphologic components of these accumulated macroforms typically consist of individual mesoforms e.g. plateaus and slopes. These formations arise from the accumulation of economically (so called) valueless materials, often produced during mining operations (Lóránt, 2012). Various shapes of dumps can develop-curved, fan and round-shaped, created during the bankfill operations in quarrying. The shape of a positive form is influenced by factors e.g. the original ground surfaces, methods of accumulation and the physical properties of the dumped materials. Cone-shaped, truncated cone-shaped and terraced dumps are amongst the most common configurations encountered (Lóránt, 2012). Table 1 provides several examples of studies on coal dump from a geoscientific perspective.

For more than 200 years, there has been widespread coal mining in the Paschim Barddhaman district of West Bengal (India), especifically in the Asansol-Raniganj tract. In 1774, commercial coal mining began in the Raniganj block of present-day Asansol, India. Besides few privately run coal mines, West Bengal has got 107 coal mines run by the Eastern Coalfield Limited (a division of Coal India Limited). Open cast mining eventually resulted in a significant dumping ground in nearby areas of mines. With time they formed a typical anthropogenic landform that got reframed by subsequent human activities in conjunction with natural erosion induced by rainfall and slumping. The primary objective of this work is to understand the geomorphologic attribute of anthropogenic landforms in the dump sites.

Organic matter from coal waste is the main source of organic compounds found in coal-waste dump water in thermally active locations. Phenolic chemicals e.g. ketones, organic acids, and Polycyclic Aromatic Hydrocarbons (PAHs)—most concentrated in coal-waste dump water—are the soluble byproducts (Fabianska et al., 2020). Al, B, Ba, Ca, Cd, Cr, Cu, Fe, K, Li, Mg, Mn, Na, P, Pb, S, Si, Sr and other elements have been found in coal-waste waters in many cases around the world. These concentrations are

Table 1 Examples of slope stability studies on coal-waste dump sites

Serial no.	Authors	Study area	Key approach	Key conclusion
1	Chaluya et al. (1999)	Dhanbad, Jharkhand (India)	Numerical modelling to assess the increase in stability and comprehend how plants stabilises the dump slope	Grass roots considerably raise the dump slope's safety factor from 1.2 to 1.4, contribute favourably to long-term stability
2	Chauliya et al. (2000)	Katras area of Bharat Coking Coal Limited, Jharkhand (India)	Measurement of dump geometry was conducted using an electronic distance metre (EDM). Standard procedures were used in both field and lab investigations to ascertain the physico-chemical characteristics of the dump material. Jack shear testing was used to determine the *in-situ* shear strength characteristics of the dump material both before and after revegetation	The stability of coal mine overburden dump slopes greatly depends on the presence of grass and tree roots. Roots provide mechanical support to the waste materials. The root matrix also strengthens the dump material's shear strength, which raises the dump slopes' long-term stability
3	Kasmer and Ulusay (2006)	Central Anatolia, Turkey	Limit equilibrium analysis is performed to analyse slope stability	This circumstance suggests that when dumping is done in line with current practice and when the creation of excessive water pressure in the piles is not permitted, spoil pile instability would not be expected. Critical floor inclination in the south pit is ~5° based on the stability of the spoil pile
4	Verma et al. (2011)	Wardha Valley Coalfield, Nagpur, Maharashtra (India)	Rock mass classification schemes, slope mass rating, and kinematic analysis of slopes using stereonet	The rock mass is partially stable to unstable according to the SMR investigation at various sites, with a failure probability of 0.4 to 0.6 (SMR class III to IV), which is further supported by kinematic analysis

(continued)

Table 1 (continued)

Serial no.	Authors	Study area	Key approach	Key conclusion
5	Kainthola et al. (2011)	Nagpur, Maharashtra (India)	The physico-mechanical parameters of the dump material were ascertained by testing representative loose samples that were taken from the site. For the study of complicated geometries, stress modelling and material behaviour, the finite element code (FEM) was utilised	When the dump angle was reduced while maintaining a constant dump height of 75 m, the factor of safety increased logarithmically. Due to the dump's poor geo-mechanical strength, it was advised to maintain the flatter slope of 25° with a height of 75 m. The dump slope produced a *factor of safety* (FOS) of 1.3 when at 25° and at 85 m height
6	Muthreja et al. (2012)	(Numerical modelling)	Application of geo-grid reinforcement techniques, waste dump numerical and physical modelling for stability analysis	Higher dumps that can hold significant overburden can be created with the use of geo grids
7	Tripathi et al. (2012)	Dhanbad, Jharkhand (India)	Biological and chemical analysis methods, bio-stability analysis method, finite difference method (FDM) are applied for stability analysis	Long-term revegetation was shown to have an indirect effect on soil fertility status in mine spoil and a direct influence on dump stability. Major contributions to the ecological regeneration of the mine spoil are made by microbial and plant biomass
8	Rai et al. (2012)	Modelling, of no specific study areas	Sensitivity analysis has been done for the dump slope's geometrical and geotechnical factors	Based on the findings, it can be inferred that friction angle is a more sensitive characteristic than dump material cohesiveness. The slope angle and height of dragline dump are extremely sensitive Height of main dump and thickness of coal rib are the least sensitive factors, while gradient of the seam and thickness of coal rib are moderately sensitive

(continued)

Table 1 (continued)

Serial no.	Authors	Study area	Key approach	Key conclusion
9	Verma et al. (2013a, b)	Wardha Valley Coal Field, Maharashtra (India)	Finite Element Method (FEM)	The Factor of Safety (FOS) decreases significantly as the dump slope's height rises. FOS depends on the kind of material and its geomechanical characteristics; however, in this case, the dump material mostly consists of shale, carbonaceous shale, and sandstone
10	Verma et al. (2013a, b)	Wardha Valley Coal Field, Maharashtra (India)	On a 32 m high cut slope, a 2D numerical simulation is utilised. Hoek–Brown strength parameters were developed and included within the model	The factor of safety was determined by the 2D analysis to be within a narrow range (0.931–1.067). The analysis has made the cut slope unstable to extremely critical, as evidenced by the rock fragments from the cut slope constantly spalling
11	Cho and Song (2014)	Heungjeon-ri, Dogye-eup (South Korea)	To examine the behaviours of both the waste dump slope and the naturally occurring slope underneath, wire sensors, a rain gauge and inclinometers were positioned at the atop the waste dump slope and in the naturally occurring slope beneath the trash dump	The monitored data showed that due to rainwater seepage into the ground during, the deformation at the peak of the waste dump's slope gradually grew until eventually converging. Furthermore, accumulation of rainwater had an impact on the natural slope underneath the waste dump's horizontal distortion
12	Rahul et al. (2015)	No specific study area	Artificial neural network (ANN) used to determine coal mine's FOS for the dump slope	ANN may predict the dump slope's safety factor more accurately than numerical modelling

(continued)

Table 1 (continued)

Serial no.	Authors	Study area	Key approach	Key conclusion
13	Liu et al. (2016)	Shanxi province (China)	The Normalised Difference Vegetation Index (NDVI), mixed pixel decomposition, variation trend computation and slope stability understanding transition matrix were used	The post-reclamation vegetation covering in the dumps is rather stable, as per the stability study of plant coverage succession and its recovery following a fire
14	Koner and Chakravarty (2016)	Wardha valley coal field (India)	The gathered samples were studied for geotechnical factors-grain size distribution, soil permeability, compaction parameters, shear and normal strength characters, etc.	The examinations of the three distinct types of overburden geo-materials showed that the shear strength characteristics for the running dump materials were the lowest of all the 11 sites studied
15	Behera et al. (2016)	Bhubaneswari mines, Odisha (India)	In order to comprehend slope instability, the Limit Equilibrium Method (LEM) was utilised	Rainfall infiltration-related increases in pore water pressure account for the majority of dump failures in the study region
16	Bednarczyk (2017)	Zloczew (Poland)	For the purpose of designing open pits and spoil dumps, slope stability analysis was conducted using the Shear strength reduction method and Flac/slope v.7 codes	Low strength clayey soils, paleo-landslide zones and structural surfaces may all be potential locations for ground movements The results portrayed that the factor of safety (Fs) ranges 0.75–1.65 for the pit and 1.12–1.60 for the dump

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Table 1 (continued)

Serial no.	Authors	Study area	Key approach	Key conclusion
17	Martín-Moreno et al. (2018)	Poveda de la Sierra–Peñalén Mining District (east-central Spain)	Slope stability analysis was conducted through topography of waste dumps and characterisation of substrata, quantification of silt captured by check dams, quantification of erosion from waste sites, and examination of precipitation and its connection to the process of filling check dams	Long, steep slopes with highly erodable materials were validated by topographic and substrate property analysis. It became out that the check dams were ineffective in reducing sediment loads
18	Rajak et al. (2021)	Mand Raigarh coalfield, Chhattisgarh (India)	Different percentages of fly ash were combined with overburden material to assess different geotechnical properties. In order to determine the ideal dump height and evaluate the stability of fly ash mixed overburden dump, numerical modelling utilising the finite difference approach was conducted	When 20% fly ash is added to the overburden (OB) maximum unconfined compressive strength and cohesion values are shown. The stability study indicates that, with 10% fly ash added to the OB material, the ideal dump height is 55 and 50 m for 35° and 37° slopes, respectively
19	Igwe and Chukwu (2019)	Enyigba (Southeastern Nigeria)	Using GeoStudio® 2012, a program created by Geoslope International Limited, stability analysis was performed and the geotechnical characteristics of the slopes were examined	One of the elements impacting all types of mass wasting is clay plasticity on moisture absorption, which is shown by the presence of swelling mineral (illite) in soil material, as proven by X-Ray Diffraction (XRD)

(continued)

Table 1 (continued)

Serial no.	Authors	Study area	Key approach	Key conclusion
20	Li et al. (2020)	The Wulanhada (WLHD) coal mine, the Liulingou (LLG) coal mine, and the Jinzhengtai (JZT) coal mine, in Jungar Banner (China)	Wiener index (H′), Simpson index (D), Pielou index (J) and Margalef index (Mg) were applied for the ecological stability analysis	Plant community and the recovery of soil properties could benefit from ecological restoration in mining areas
21	Gupta et al. (2021)	Review paper		Multiple failure modes can coexist within the same dump due to the heterogeneous nature of the material Numerical modelling enables accurate simulation of input parameters e.g. rainfall, groundwater, earthquakes, blasting, material variability, complex and uneven geometry, interfaces, discontinuities, external loading
22	Raha et al. (this work)	Dhanbad and Durgapur, Jharkhand and West Bengal (India)	Total station survey is conducted on the dumpsite for terrain analysis and field photographs are interpreted	The dumpsites portray various segments of slopes- free face, convex and concave with the events of slope failure. Vegetation is a slope-stabilizing factor

typically much higher than the legally permissible concentration levels in wastewater discharged into surface waters and the ground (Djinovic & Popovic, 2007; Lewińska-Preis et al., 2021).

Adibee et al. (2013) report that parts of the downstream farmlands around Karmozd coal mine, Iran, have been devastated by recent flooding caused by dumping waste. The loss of agriculture and the ensuing risks to public health/environment are evident. As per Bian et al. (2009), following a period of continuous rain, inner vapour pressure built up in the mining waste dump of Pingdingshan coal mining company's No. 4 coal mine (China), which detonated on 15-May-2005. Eight locals lost their lives in the explosion, 123 others suffered injuries and 18 residents' homes were destroyed.

A common blueprint for peace and prosperity for people and the planet, both now and in the future, is provided by the 2030 Agenda for Sustainable Development, which was accepted by all United Nations Member States in 2015 (https://www.coursehero.com/file/226174032/ASSIGNMENT-HRMdocx/). The 17 Sustainable Development Goals (SDGs), which represent an urgent call to action for all nations—developed and developing—in a global partnership, are at the centre of it.

Understanding the harmful environmental issues in dump-site locations is crucial for achieving the SDGs of clean water and sanitation, and protecting life on land.

2 Study Area and Dataset

Four dump sites near Damagoria Colliery Bharat Coking Coal Limited (BCCL) and one near Mugma were studied (Fig. 1). Field surveys were conducted to gather primary data. Total station surveys were employed to study slopes in the dump sites.

3 Methodology

The dump site at the studied three locations (Fig. 2) was surveyed with total station (Leica TS07) in three segments. Latitude, longitude and elevation data were collected**.** The data has been processes on ArcGIS 10.4 (2016) platform and Surfer 11.0 (2013) to prepare digital elevation models (DEMs) and draw cross sections.

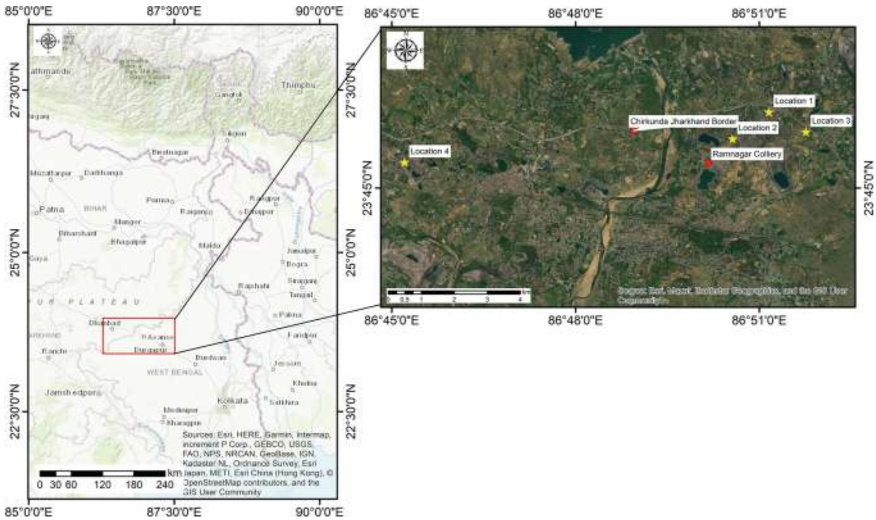


Fig. 1 Location map of the study area; locations 1–4 have been plotted

Fig. 2 Dump site at location 1. **a**. Slumping along the slope. Slumped material deposited at the base. **b**. Slab failure at the toe of the slope. Minor gullies developed along the slope. **c**. Overall geometry of the slope is convex. Two mining sites noted. **d**. Predominance of angular- boulders at the dump site

4 Results

The dump site at location 1 (Fig. 2) typically exhibits a convex slope with a steep gradient of 70° (Fig. 2a). The loosely packed materials on this slope are prone to slumping, particularly at the base of the slope. The material that slumps accumulates further downhill in a heap. Rain has created several gullies on the slope (Fig. 2b). Steepening of the slope exacerbates slope failure at its base. Interestingly, the dump site is still being utilised for mining activities. Such unauthorised and unplanned quarrying is making slopes unstable, leading to more frequent slab failures and slumping. Angular boulders are predominantly observed throughout the area.

The dump site at location 2 (Fig. 3) also exhibits flow paths/gullies on its slope. Notably, coarser materials dominate the lower parts of the slope, while finer materials prevail in the upper segment where shrubs/grasses exist. No slumping/slab failure are observed. In contrast, location 3 (Fig. 4) displays a different topographic expression. This dump site is partially covered with thick grasses and shrubs, indicating a stabilised slope and is devoid of slab failure/slumping. Several flow paths are documented across the slope.

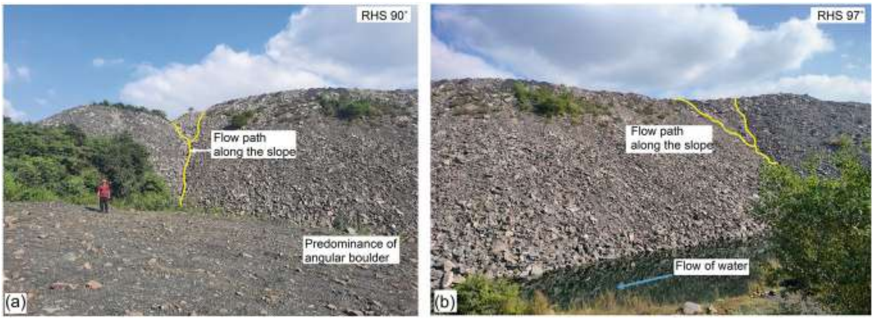


Fig. 3 Dump site of location 2. **a**. Mostly composed of angular bouders. Convex slope is obsereved with the development of flow path along the slope. **b**. Vegetation grown over the dump site along with the development of flow path on the slope

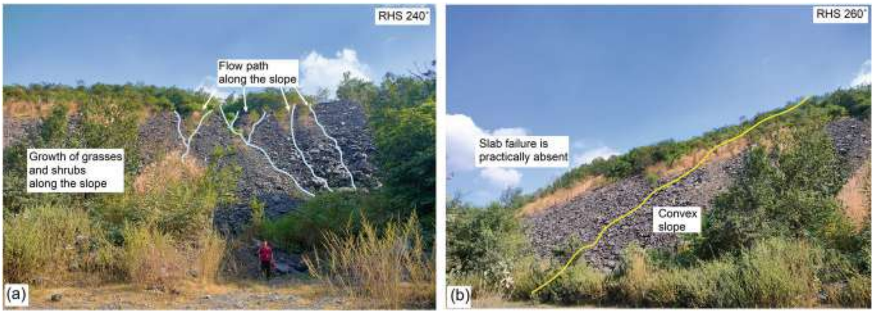
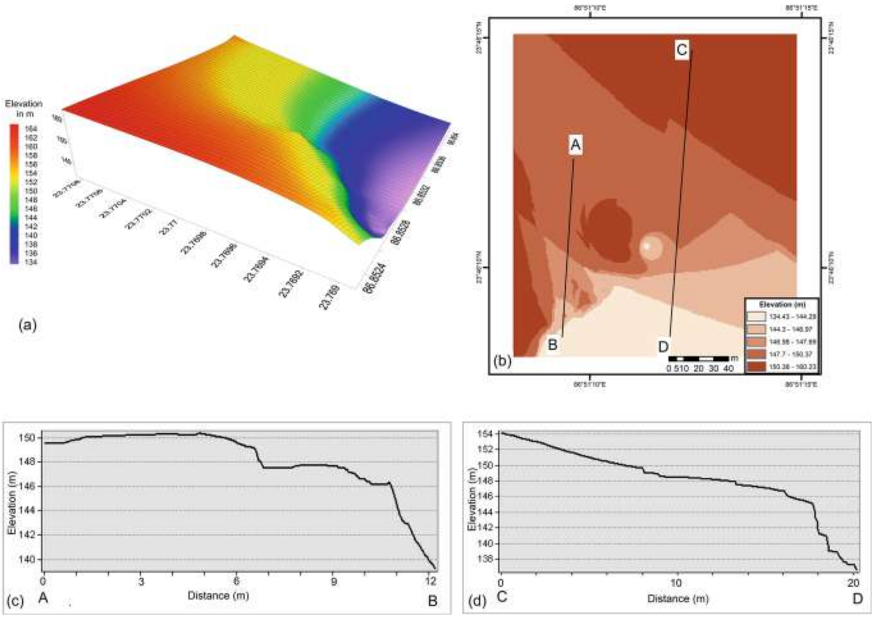


Fig. 4 Dump site at location 3. **a**. Thick vegetation on the slope with multiple flow paths. No evidence of slumping/slab failure. **b**. Convex slope with ~50° gradient

The dump site at location 4 (Fig. 5), is situated close to a mining site. The dump site is relatively new and demonstrates a less altitude. The topography is a convex slope, which got stabilised due to the growth of thick vegetation. The dumped materials exhibit poor sorting, with angular boulders being predominant. Segment 1 at location 1's DEM illustrates various slope segments (Fig. 6a, b). Cross sections (Fig. 6c, d) depict steep slopes on the flanks. Slopes range between 70–80°.

At the second segment of location 2, there is a contrast in slope profile characteristics. The DEM (Fig. 1, Repository) reveals a dome-shaped terrain with a slightly concave slope on the flank. The AB section (Fig. 1, Repository) delineates three distinct slope segments from the top to the toe. Starting with a convex slope at the top, it transitions into a free face at an altitude of 141.5 m, followed by a gentler convex slope, and finally a concave slope at the bottom. The CD profile (Fig. 1, Repository) demonstrates a steeper slope (60°). Segment 3 at location 2 (Fig. 2, Repository) indicates a higher altitudinal profile with steeper gradient. The AB profile forms near a horizontal plane at the top, followed by steep (70°) free face slope segment of a height of ~50 m. The base of the slope shows a convex-upward geometry, which can

Fig. 5 **a**. Dump site of location 4. **b**. Materials are dumped in the adjoining areas and got covered by grasses. **c**. Convex slope of ~50°, covered with thick vegetation. **d**. Poorly sorted materials defining the convex slope with gentle gradient (30°)



Figs. 6 Topographic expression of segment 1 of the dump site at Location 1 (23.768911°N/ 86.852588°E). **a**. 3D view of the slope segment and surface expression prepared with Surfer 11.0. **b**. Digital elevation model. **c**. Cross-section along AB. **d**. Cross section along CD

be attributed to the deposition of slumped materials from the free face segment. The CD section (Fig. 2, Repository) exhibits similar pattern of slope segments. The flat top is followed by steep (80°) free face slope, which is susceptible to slumping/slab failure.

5 Discussions

This geomorphic study helps to understand the nature of an anthropogenic landform. The primary natural microforms found on dumps are rainwater channels etched into slopes, typically arranged in radial patterns on cone-shaped or truncated cone-shaped dumps. The gradient of slope additionally provides insight into the mechanism of slumping and slab failure. Vegetation developed at places has stabilised slopes.

During the monsoon season, the channels that have grown across the waste slopes transport water. It is important to note that the water carries the finer debris down to the slope. There is strong possibility that this water will combine with the neighbouring clean source of water (as pointed out in another area by Wohl (2006). Therefore, it is critical to take the required steps to safeguard and conserve the clean water sources in order to achieve the SDG of clean water and sanitation.

Locals in the dump sites under study continue to mine in order to survive. To prevent any tragedies, it is crucial to understand the slope failure at dump sites. The casualties (Indian review from Mohanty et al., 2022) and land degradation are to be checked in order to fulfil the SDG of life on land.

At Nigahi Open Cast Project (OCP), Northern Coalfields Limited (NCL), grass bedding and seed ball stabilisation of overburden dumps have been actively pursued for the past few years by the Coal India Limited, Govt. of India.

In order to stabilise the slopes of the dump sites, we propose the following landform guidelines- (i) reduce the gradient of the linear slopes of the four main waste dumps by removing materials from their upper reaches; (ii) avoid mining at the base of the slope to prevent slumping (community awareness is required in this regard); (iii) adopt natural slope stabilising methods, such as planting native vegetation on the slope.

This preliminary investigation on the dump slope expands the possibilities for a more precise analysis of the slope failure by utilising model simulation (Bednarczyk, 2017; Mutherja et al., 2012; Verma et al., 2013a, b), comprehending the properties of the sheer stress of the materials dumped (Chaluya et al., 2000), identifying the type of grass (Li et al., 2020) and measuring the lengths of grass/vegetation roots required to stabilise the dump slope (Chaluya et al. 2020).

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