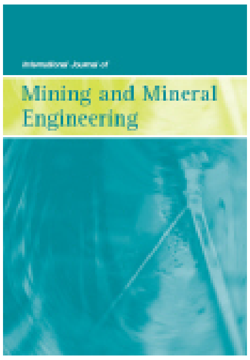

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A review on stability analysis of coal mine dumps

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Abstract: Opencast mines are increasingly extracting deeper coal seams in large quantities, leading to a rise in mine depth and generation of substantial waste. Disposal of this waste becomes challenging due to the need for additional land, resulting in dumping excess waste on existing dumps, posing risks of dump failure, property damage, and loss of life. This paper aims the critical review of the stability of dump slope structures that are present on the weak or disturbed foundations which further leads the dumps to fail. Many researchers have concentrated on the irregular base, loose material presence in the foundation, sloping floors, improper compaction at the foundation level, presence of black cotton soil, etc., stating load of the dumps over the weaker foundations exerts more pressure on the foundation and causing the dumps to fail. It synthesises key findings on stability analysis approaches, design criteria, optimisation techniques, and critical parameters involved in numerical modelling-based design for secure dump slope structures.

Keywords: overburden dumps; dump stability; influencing parameters; numerical modelling; factor of safety.

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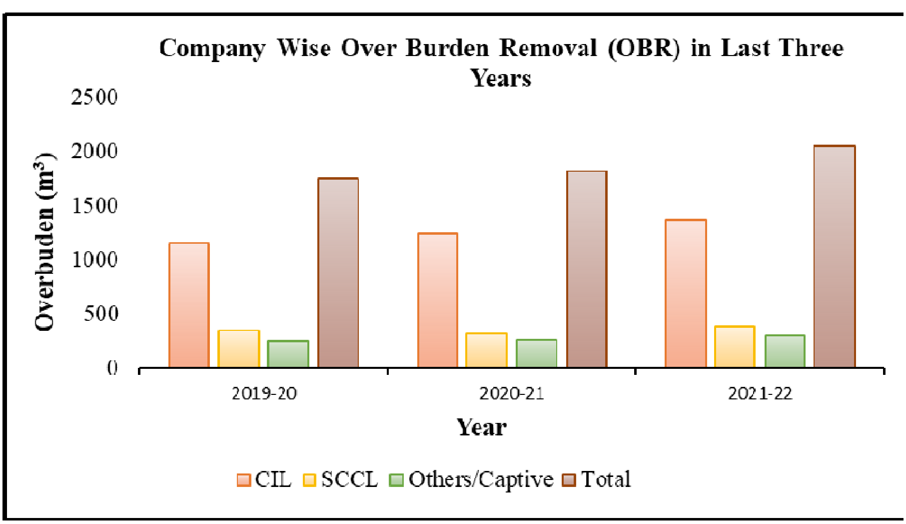
1 Introduction

For centuries, coal has supported economies and been used to power and construct infrastructure in contemporary society. The World Coal Association (WCA) (2020) reports that the demand for coal in industrial applications has nearly doubled since 2000 and is expected to continue rising until 2040. In 2019, global coal production reached approximately 7.1 billion tonnes, with sustained investment programs and technological advancements. Opencast coal mining produces a significant amount of overburden which will be dumped as dumps in and around the mining region (Singh and Narzary, 2021). It is important to assess the stability of dumps to maintain them under a safe condition in order to avoid problem from failures. In recent years, opencast mine productivity has significantly increased. The improvement in opencast mining technologies and the rising demand for metals and minerals across a variety of industries are the reason for the market's growth prospects. According to Globe Newswire (2019), reports and data stated, the global opencast mining market is anticipated to reach USD 32.92 billion by 2026. Although opencast mines are quickly meeting the demand for minerals, a significant amount of OB/waste rock material is also being produced simultaneously due to increased stripping ratios (Koner and Chakravarty, 2016). The overburden generated by different companies in India is shown in Figure 1 company-wise overburden removal in the last three years (Ministry of Coal, 2022).

Human activities like excavation and dumping methods show impacts on the physical and geotechnical properties of the waste dumps. Long-term stability of waste dumps becomes important for safe restoration activities (Masoudian et al., 2019). Selecting an effective stability analysis approach, as well as developing proper dump slope monitoring system, need knowledge of basic types of mine dump failures.

Figure 1 Company-wise overburden removal in the last three years (see online version for colours)



Source: Ministry of Coal (2022)

One of the most important factors in opencast mine planning is the selection of an appropriate site for dumping waste material during the life of the mine. The mine waste generated is most likely dumped on the same site due to a deficiency of a proper waste management system. The location of the waste dump site significantly influences both the capital and operating costs of a mine (Gupta and Paul, 2015; Hekmat et al., 2008). Under limited lease areas and an increase in coal seam depth, the height of the overburden dumps increases and may cause the dumps to slide. As a result, it has increased the risk of dump failure, gully erosion, and other environmental issues (Gupta et al., 2021; Nayak and Dash, 2019). Based on the geology and terrain of the mine location, the overburden dump may have a single or multiple decks. These dump slides can occur in many different ways, gradual or fast, with or without apparent provocation (Koner and Chakravarty, 2016). Excavation or undercutting the foot of an existing dump slope is the most typical causes of slides (Campbell, 1992). Figure 2 represents an overview of the dump slope which is formed in decks with generated waste material from the opencast mine.

Figure 2 An overview of the dump slope (see online version for colours)

Source: Gupta et al. (2021)

The geotechnical properties of waste dump material and the dump foundation (i.e., floor) are important in the development of a safe slope structure. The basic material's fragment size ranges from extremely tiny clay particles to very coarse rock pieces like a boulder. Numerical modelling is useful in simulating the behaviour of such complicated materials and providing the optimum solution for real challenges (Eberhardt et al., 2004; Griffiths and Marquez, 2007; Jhanwar and Thote, 2011; Jing and Hudson, 2002; Tang et al., 1998; Griffiths and Lane, 1999; Nogueira et al., 2012). The right attention to the mine overburden dump management is required for the smooth execution of mining activities.

The improper dumping of overburden materials can result in the instability of dumps, affecting production rates and the safety of mining operations. Mine dump stability is vital from both the economic and safety point of view (Chaulya et al., 1999; Rajak et al., 2020).

A literature review is presented in this article that describes the various research studies conducted on the slopes of overburden dumps. The review article is divided into three sections. The first section is related to the influencing parameters of the dump stability (geometrical, geotechnical and weathering factors). The second section focuses on the floor condition of overburden dumps and its influence on dump stability. The final section deals with numerical studies of the stability of overburden dumps.

2 Parameters affecting dump slope stability

Adoption of opencast mining has been increasing and the problems associated with overburden dumps, the cost of mining and environmental and safety hazards have become a challenge to the industry. Therefore, attention is required to critically analyse the factors affecting the overburden dump stability. Fischer and Huggel (2008) stated that the factors can be broadly classified as topographical, geomorphological, geological, hydrological, and various other physically-based elements. Figure 3 shows the parameters affecting the stability of overburden dumps (Fossil Energy and Carbon Management, 2006).

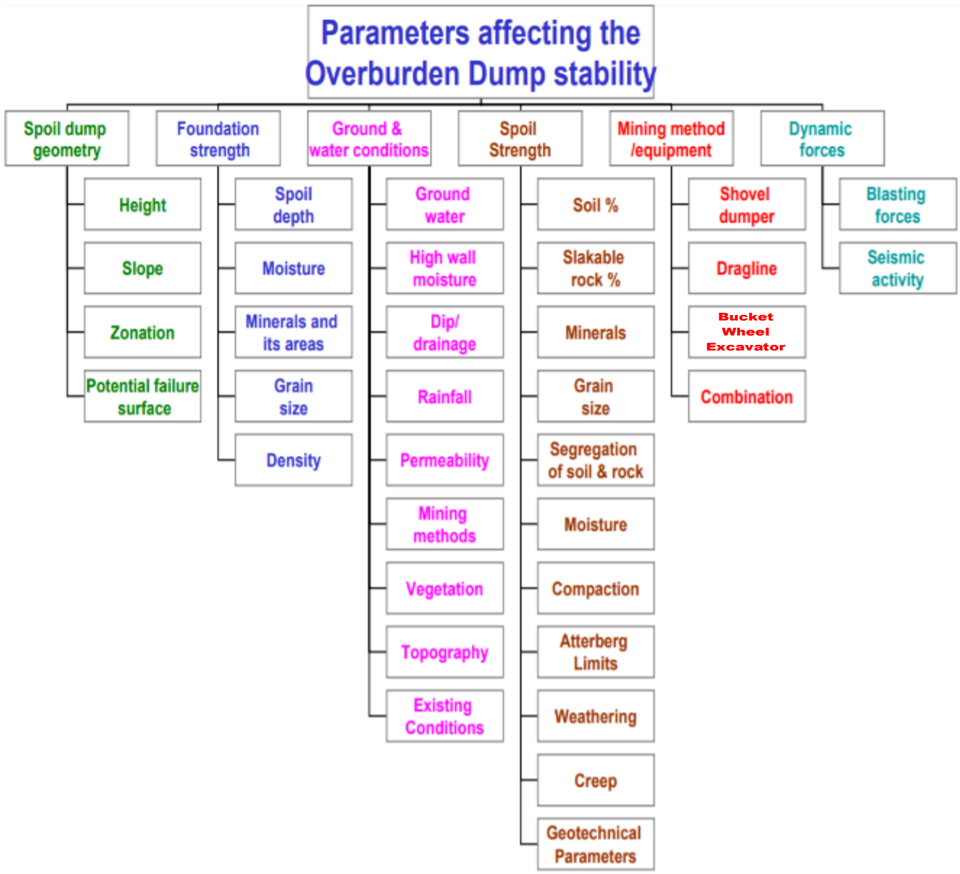
Several causes for overburden dump failures include overburden dump material and foundation failures. The most common factors affecting dump failure are geometry of slope, material properties and forces acting on the slope (Amarsaikhan et al., 2018). According to Kainthola et al. (2011), there were instances of dump failure in Wardha Valley attributed to inadequate dump geometry. The physico-chemical composition of the waste rock, the dumping techniques utilised, engineering conditions of the ground, hydrogeological conditions, and other associated characteristics contribute to the stability of a waste dump (Zou et al., 2018). Rai et al. (2012a) and Upadhyay et al. (1990) investigated the stability of the dump slopes using a finite element approach considering several characteristics like floor inclination, dump height, dump slope inclination, geological and hydrological condition, the contact between the dump material and the floor, physico-mechanical properties, etc and concluded in designing a safe and economical dump slope to avoid critical dump failure.

Rainfall infiltration increases pore pressure in slope material, reducing its factor of safety (FoS) and causing slope failure (Behera et al., 2016). The instability of the dumps is caused in numerous ways. Some of them are water seepage from the landfill, different cohesion materials, change in stress levels, vibration of the ground, dump slope angle, degree of compaction, angle of internal friction, particle size analysis, specific gravity, and permeability and dump height (Reddy et al., 2020). An investigation was conducted on the stability of mine waste dumps considering high rainfall effects (Jhanwar and Thote, 2011) and an empirical relationship was proposed from numerical modelling for calculating the FoS of the waste dump (Yellishetty and Darlington, 2011).

$$FoS = 0.027C + 0.04\phi - 0.03DH - 0.083PWP + 0.65 \tag{1}$$

where *FoS* is the factor of safety, *C* is cohesion (kPa), ϕ is the angle of internal friction (in degrees), *DH* is the dump height (m) and *PWP* is pore-water pressure (m).

Figure 3 Parameters affecting overburden dumps (see online version for colours)



Source: Fossil Energy and Carbon Management (2006)

Cohesion and angle of internal friction are two key parameters that are considered in slope stability. The slope is said to be unstable when the cohesion and angle of internal friction in the shear strengths of the slope get decreased in the shear strength reduction (SSR) technique (Hammah et al., 2005). The stability of dumps relies on mobilising the residual friction angle of the dump material, which can result from operational strain or presence of water (Poulsen et al., 2014). Verma et al. (2013) found that in an opencast coal mine in Wardha Valley coal field, Maharashtra, increasing dump slope height significantly decreases the factor of safety (FoS) of internal dumps. A case study was undertaken to assess the factors causing dump failure in the western section of the Jayant opencast mine (Sharma and Roy, 2015). The factors that influenced the cause of the accident were the overall slope angle (45°), overall dump height (85 m), seepage water pressure within the dump and an earthquake tremor prior to the accident. These factors lead to slide 1,46,000 m^3 volume of dump slope. Dump stability is one major issue to be considered and maintained to avoid hazards in and around the mine. There are many factors that cause the dump unstable and lead to a huge loss of men/machinery or both. According to Rajak et al. (2020), multiple instances of coal mine dump failures were documented. Table 1 shows some of the dump failure cases occurred in India during the past 25 years (Bishwal, 2019).

Apart from dump geometry and ground conditions, the dynamic forces also affect the dump stability which should be considered. Ground vibrations generated due to blasting creates annoyance to the nearby residents and damages the structures like buildings, rock mass, waste dumps, etc. during the mining activities (Valdivia et al., 2003). Cracks developed over the dumps results more unstable dumps. The width of the cracks increases when natural or blasting vibrations come into the frame. It was found that cracks near and around the dump, will affect the stability of the dump slopes (Bharati et al., 2020; Huang, 2014).

Table 1 List of major coal mine overburden dump failure in India

Date	*Location*	*Cause*	*Impact*
August 1995	Hindustan Lalpeth (WCL)	OB dump slope slide from a height of 25 m due to rainfall	-
June 2000	Kawadi opencast coal mines (WCL)	Slope failure of 31 m high overburden dump	10 people killed
December 2008	Jayant opencast coal mines (NCL)	The dragline dump slope failed	5 people killed
January 2009	Jayant opencast coal mines (NCL)	Dump failure	4 people killed
June 2009	Sasti opencast coal mine (WCL)	73 m height OB dump failed	2 people killed
May 2005	Lignite mines (NLC)	Dump slide in the dump yard of the bottom bench	The dump was moved down to 25 m
August 2013	Basundhara coal mines (MCL)	Dump failure due to rainfall	14 people killed
July 2014	Dhanpuri Opencast mine (SECL)	Backfilled overburden slid into sump	2 people killed
May 2015	Khadia OCP (NCL)	Internal dragline overburden dump failed over a length of 130 m.	Burying of 2 dozers, 1 excavator and 1 rope shovel
December 2016	Lalmatia coal mines (ECL)	Failure during removal of loose OB.	23 persons reportedly buried in OB dump slide
July 2019	Bharatpur OCP (MCL)	Failure possibly due to blast induced ground vibration. Debris of about 100 feet depth was slid.	4 miner dead, 10 injured in the landslide caused by OB dump failure.

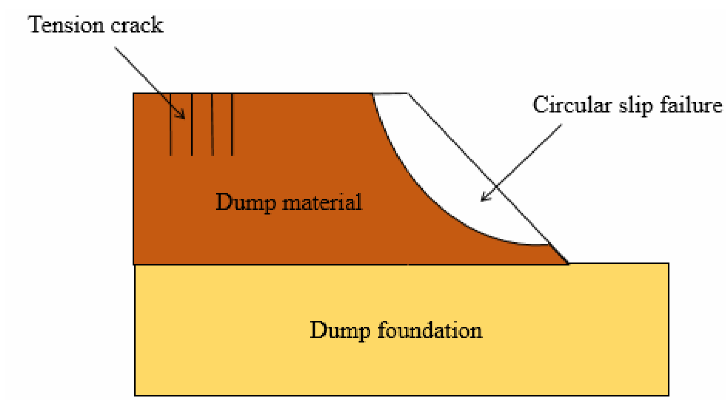
Source: Bishwal (2019)

From Table 1, it understands that the dump failures took place due to over height, rain water infiltration, improper compaction, and ground vibrations caused due to blasting and these can be controlled by taking necessary steps.

3 Stability of dumps on weak foundations

The floor of the dumps is also one of the major parameters to be considered for the stability of the overburden dumps. The formation of dump slopes on the weak layer of the foundation is very problematic. In general, foundation condition is critical component in ultimate dump stability and a schematic diagram for a dump slope is illustrated in Figure 4. The most common source of dump instability identified is a faulty foundation (Chaulya and Prasad, 2016). The weaker base, the sloping floor and irregular topography cause the dumps to fail more easily resulting in dump unstable condition (Muthreja and Yerpude, 2012). The stability of an overburden dump over the manmade sludge weak base can cause the overburden dump instability. Stress state modelling of an overburden dump on the weak base was modelled and the stability of the dump was analysed thoroughly (Bakhaeva et al., 2016). *Highwall mining* is very similar to auger mining in its concept, where the entry into the coal seam is initiated from the highwall of the ultimate pit limit. The stability of the roof along the highwall is one of the major challenges in highwall mining. A numerical study was carried out on different gallery widths and their effect on the highwall is studied. It is observed that the higher gallery width having more stress and strain values and lower FoS (Chandar and Kumar, 2014).

Figure 4 Schematic representation of dump slope (see online version for colours)



The geologic process and physical properties affect the shear strength of the compacted natural soil. The natural soil was categorised into four friction angle groups based on the relationships between strengths, deformation behaviour, geologic origin and physical properties (Bareither et al., 2008). The base of Makardhokra – II opencast mine overburden dumps is covered with black cotton soil that extends 20 meters into the ground and it is analysed to study the strength of the base. In the event of rainfall, the strength of such a base was found to be very low. The study results suggest the construction of Gabion walls is more useful and eco-friendlier as well, for growing vegetation (Shruthi et al., 2019). Similar numerical studies were conducted by considering 2–10 m of black cotton soil layer with five different scenarios at the foundation level (Verma et al., 2023). It was found that the replacement of black cotton soil with a suitable material near the toe would improve the stability of the dumps. Roy (2008) investigated external dump failure at Sonepur-Bazar opencast coal mine, at the toe of the external dump caused due to a combination of weak foundations. The suggestions from the studies include to enhance stability separating of clayey soil from rocks during dumping, implementation of garland drains on external dumps to prevent toe water accumulation, and consider gabion walls at the dump's base to prevent floor heaving.

A study was conducted on the stability of the overburden dumps by constructing a rock-filled trench to stabilise the dump. The results concluded that the maximum thickness of 10 m surface of the weak floor is optimally trenched at the final toe (Sekhar et al., 2021).

One of the case studies wherein two very large slip failures of in-pit coal mine waste dump in weak, slaking, claystone and siltstones in equatorial high rainfall areas are explained by (Pells, 2016). The results of the studies showed that the weak surface of the dump is designed in accordance with stress parameters with the residual friction angle in a sheared basalt layer. The final geometry failure of the dumps will be controlled by undrained shearing. Different geo-mining variables have been examined by Sharma et al. (2020) to determine the stability of pillars under overburden dumps in Bord and pillar mines and it was concluded that the load on the pillar increases with the increase of depth of the cover and height of the dump and leads to the pillar failure.

4 Numerical studies on the stability of the dump slope

In order to assess stability and design a safe and optimal dump slope structure, numerical modelling is the preferred technique. During the stability analysis process, it considers the stress-strain relationship as well as the material strength. It also provides a series of parametric studies that can be performed with precision for a wide range of geometry, geotechnical parameters, and external disturbances useful in the design of stable and optimal dump structures. There are many other factors that influence the dumps to fail, other than geometry and geotechnical parameters like the weak floor of the dump, improper compaction of the dump material and pore water pressure. There are some of the other factors that are coming into picture and causing the dumps to fail like the interface between dumping material and dumping area, the strength of the dumping area, and the presence of weak material in the dump material composition, etc.

Limit equilibrium analysis is used in many applications with basic loading conditions and simple slope geometries. Slopes with complex geometry, nonlinear material behaviour, in-situ stresses, the presence of pore pressures, seismic loading, etc. are dealt successfully with the finite element method (Huang, 2014). Eberhardt et al. (2004) employed various numerical techniques, including continuum, discontinuum, and hybrid methods, to analyse the development of slide planes and weakening of internal strength in massive natural rock slopes. The Dagushan waste dump in China, which is more prone to deformation was studied based on the limit equilibrium theory under dumping, vibration, basement softening, and parameter sensitivity of the influencing factors (Wang et al., 2021). It was found that FoS decreased from 1.238 to 1.129 because of the weakened basement of silty clay. Similarly, the dump stability of Talcher Coalfield was analysed using the limit equilibrium method and it was reported that the dump landslide occurred mainly due to rainfall infiltration (Behera et al., 2016). The stability analysis of Singrauli mine overburden dumps was carried out using a two-dimensional finite element analysis using the strength reduction method (Banerjee and Chawla, 2017). The failure surface and displacement of the dump slopes are observed when the rainfall weathering condition is considered to cause slope instability. The rainfall caused an increase in pore water pressure and voids, which decreased the shear strength of the dumps. An investigation was carried out by Sekhar et al. (2021) on dumps with different heights (60 m, 75 m, 90 m, 120 m) and a trench of 120 m wide with a depth of 5 m, where a rock-filled trench was found to be more effective when the trench depth corresponded to the floor thickness.

A distinct numerical modelling technique known as the finite difference method (FDM) is used in studying the distribution of weak material to the dump slope. Research-based FDM simulation work was carried out by Singh et al. (2022) where the percentages of weak material for different dump heights varied and the FoS was estimated. The simulations proved that an increase in either dump height or the percentage of weak material will decrease the FoS of the dump. The study results also showed a drastic decrease in the FoS when the dump material is mixed with the weak material. Similarly, a study was made to assess the stability of dump slopes based on the FDM method using FLAC-3D software (Rai et al., 2012b). The study also shows the utilisation of Geogrid sheets with many different combinations of spacings to observe their effect on the stability of dumps. The slope angle can be increased from 45 to 60 by using geogrid at 1-m spacing with desired factor of safety of 1.4. Feng et al. (2015) investigated the numerical simulations of the waste dump slopes using FLAC-3D and analysed the working conditions at different slope angles, single and multiple decks. From the numerical simulation analysis, it was concluded that the multiple decks with 24° slope angle are more stable when compared to single decks with slope angle of 24° and 30°, as the single deck slopes are having a tendency to slide along the basement of the weak strata.

Bharati et al. (2022) predicted the FoS using soft computing-based approaches such as artificial neural network (ANN) and multivariate regression analysis (MRA) for a total of 216 dragline dump slopes considering coal rib height, dragline dump slope height and slope angle as the input variables. The proposed equation for the FoS is:

$$FoS = 2.37129 - 0.0175Crh - 0.00179Sh - 0.015881Sa \tag{2}$$

where *FoS* is the factor of safety, *Crh* is the coal rib height, *Sh* indicates dragline dump slope height and *Sa* is the dragline dump slope angle. The prediction models were assessed based on statistical parameters such as coefficient of correlation (R^2), root mean squared error (RMSE), and variance account for (VAF). The R^2, RMSE and VAF for the ANN model were 0.9996, 0.0208 and 97.69 whereas, for the MRA model, the corresponding values were 0.9769, 0.0037 and 99.92 respectively. According to the ANN and MRA analyses, *Sa* is the most crucial geometrical parameter in terms of dump slope stability among the three most sensitive geometrical parameters.

The stability of overburden dumps at Makradhokra – II opencast mine of Western Coalfields Limited was studied and numerical analysis has been performed by (Shruthi et al., 2019) and concluded that the presence of black cotton soil could cause the dumps to fail because of its swelling nature during the rainy season. Suggestions made from the study to prevent the failure of dump slopes comprise the construction of gabion walls with drainage allowing the dissipation of pore pressure. Radhakanta and Debashish (2010) used a discrete element method-based numerical technique to study the behaviour of interlocked discontinuities in the external dumps. The dumps did not show any failure behaviour at the FoS 1.67 and 1.17, but at 0.95 and 0.92, it showed failure along the slope and discontinuity plane.

The degree of influence of each parameter varies from one to another. Quantifying these parameters accurately and simulating them with precision is a tedious process. Several input parameters can be accurately simulated using numerical modelling, including rainfall, groundwater, earthquakes, blasting, variability of dump materials, complex and irregular geometry, interfaces, discontinuities, external loads, and other disturbances Further, it offers additional output parameters as well as a stability assessment for the entire dump slope structure. In addition to providing a precise assessment of unstable sections of the slope structure, contour-based output parameters such as displacement, shear strain, plasticity, and velocity profile can also be applied.

5 Conclusions

1 This article summarises the parameters that influence the stability of overburden dump slopes include the height and width of the dump, dump slope angle, geotechnical parameters like cohesion and friction angle, rainfall, and dynamic forces. Each parameter holds its own significance, and their collective influence on the dumps can significantly impact their stability. Proper consideration of these parameters is crucial for ensuring dump safety.

2 Numerical simulations are valuable tools for assessing dump slope stability accurately. They can provide acceptable values for different input parameters, aiding in making informed decisions. Three most commonly used numerical modelling techniques for assessing dump stability – limit equilibrium analysis, finite element analysis, and finite difference methods. Among them, the finite difference method stands out as highly preferable for studying the behaviour of dump material and its impact on the overall stability of the dumps.

3 Generating a large amount of overburden material coupled with limited dumping space can lead to an increase in dump slope height and complexity. These factors should be carefully managed to maintain stability also, due to the heterogeneous nature of dumps, more than one mode of failure can exist within the same dump. This emphasises the need for comprehensive assessments and monitoring of dump stability.

6 Future scope of work

The research study on this heterogeneous dump material is providing more and more scope for the researchers to work and provide some stability features of the dump slopes. Some of the identified weak points include the behaviour of the foundation material, the load-bearing capacity of the foundation, water infiltration in dumps, and the lack of consideration for underground workings and their influence on dump stability. Based on an intensive literature review, it can be concluded that there has been little to no research conducted on dump stability when old underground workings are present, leading to stress and deformation in the surrounding areas, ultimately resulting in slope failures.

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