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Sustainable Waste Management in Open Pit Mines: Rethinking Inner Dumping Practices in Modern Mining

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Abstract: Inner dumping, also known as in-pit dumping, is a waste management practice in open pit and open cast mining where waste materials are deposited within the mined-out area. While touted for its potential to reduce environmental footprint and transportation costs, inner dumping presents distinct operational challenges that can affect mining efficiency. This paper examines key operational challenges including space constraints, logistical complexities, increased operational costs, and impacts on mine design. Strategies for optimizing inner dumping practices are explored, emphasizing advanced planning, integrated waste management systems, innovative techniques, enhanced coordination, and technological investments. By addressing these challenges effectively, mining operations can enhance operational efficiency and sustainability in waste management practices. This research contributes to insights essential for improving inner dumping methodologies in modern mining operations.

Keywords: Open-pit mining, waste-material management, In-pit dumping, operational challenges.

Introduction

Mining activities, particularly open pit and open cast mining generate substantial amounts of waste materials. These sites are purposefully designed to serve as secure repositories for loose waste rock, mostly dump materials comprising of environmental degradation elements. Slopes engineered to the need, can minimize erosion by controlling the surface runoff water. One of the key activities of responsible mining operation is to minimize the ecological footprints of mining and preserving the natural resources.

An open pit mine dump can be categorized into internal waste dumps and external waste dumps (Ranjan et al., 2017). Internal waste dumps are strategically positioned within the confines of the open pit itself, effectively minimizing the distance for transporting waste materials from the extraction point to the disposal site. These dumps efficiently utilize available space within the active mining area, accommodating waste rock and overburden removed during excavation. Their proximity to the mining operations enhances logistical efficiency but necessitates meticulous planning to avoid interference with ongoing extraction activities.

Several studies highlight that inner dumping is helpful in significantly reducing the mining cost, fuel consumption, minimum disturbance to external land, and thus, lower the environmental impact of overall mining operation (Das et al., 2022; Cacciuttolo & Atencio, 2023). Several studies have developed scheduling algorithms of mine planning with main parameters of mine production, cost, space optimization, and stability considerations (Li et al., 2013; Das et al., 2022). These models highlight the trade-off between minimizing haulage costs and maintaining efficient ore access, a logistical complexity unique to in-pit dumping.

In contrast, external waste dumps are situated outside the main pit area and serve as expansive repositories for waste materials that exceed the capacity of internal dumps. Located in designated areas adjacent to the mine site, external dumps securely store large volumes of waste rock over extended periods. External dumps are integral to managing the environmental impact of mining by providing safe storage for materials that cannot be reintegrated into the natural landscape.

Both internal and external waste dumps are essential components of responsible mining practices, ensuring efficient waste management, while minimizing the ecological footprint of mining activities. However, whether within the dump or located outside its boundaries, accidents such as landslides and mud-rock flows occasionally occur, resulting in human injuries and property losses (Hasani et al., 2017).

Landslides within dump areas may result from unstable slopes or inadequate design, causing sudden movements of waste materials that endanger workers and nearby infrastructure. Yongping Copper Mine and Nanfen Iron Mine, have experienced significant landslides and debris flows, displacing massive volumes—such as 15.4 million cubic meters and 38 million cubic meters, respectively (Xu et al., 1994; Yang and Li., 2012).

The stability of slopes in open-pit mines significantly influences both mining operations and the surrounding environment, playing a critical role in ensuring safety, operational efficiency, and environmental protection. Unstable slopes pose risks to personnel and equipment within the mine, leading to accidents like rock falls and landslides, which can disrupt operations and increase costs (Gupte et al., 2013; Chen and Song, 2020; Chen et al., 2021; Song et al., 2021a; Song and et al., 2021b). Factors affecting the stability of inner dumps are geometry, height, slope angle, bench configuration, and water. Numerical simulation studies from Baganuur coal mine, Mangolia, have demonstrated that dump height and steep slopes significantly reduce the factor of safety, thus increasing the risk of slope failure (Munkhtogtokh et al., 2025).

Another, case is from Baiyinhua open pit mine, China, dumped material over weak base layer, caused some disturbance in the floor of pit, therefore, at the later stages, staged treatment was recommended to mitigate settlement challenges (Zhang et al., 2023).

In-pit dumping highlights the potential improved closure strategies and reduced long term liabilities (Cacciuttolo and Atencio, 2023). Moreover, most studies have focused on large coal and lignite mines, with limited research on non-coal open pits or operations in mountainous terrains, where narrow geometries and steeper slopes impose additional constraints.

This paper explores the various disadvantages associated with inner dumping in open pit and open cast mining, including environmental, operational, economic, and safety concerns. By providing a comprehensive analysis, this paper aims to inform mining operations and policymakers about the potential challenges and encourage the development

Table 1. Factors affecting inner dumping at open pit mining operations.

Category	Factor	Description / Importance
Geotechnical Stability	Dump Height & Slope Angle	Higher dumps and steeper slopes reduce stability; must be optimized for safety.
	Floor Strength & Treatment	Weak base layers may cause settlement or instability; floor treatment is often required.
	Material Properties of Waste Rock	Grain size, cohesion, and moisture content influence compaction and slope stability.
Mine Planning	Availability of Void Space	Inner dumping can only begin when mined-out areas become available.
	Synchronization with Production	Waste scheduling must align with ore extraction to avoid blocking access to ore.
	Haulage Distance & Transport Logistics	Reduced haulage cost is a key benefit, but requires careful planning of haul roads.
Environmental Factors	Land Use Reduction	Inner dumping minimizes external land disturbance and preserves ecosystems.
	Water Management	Dump design must prevent infiltration and potential acid mine drainage.
	Dust & Air Pollution	Dust control is essential, especially in arid environments.
Economic Considerations	Operating Costs	Reduced haulage lowers costs, but geotechnical treatments and monitoring add expenses.
	Long-Term Closure & Reclamation Costs	In-pit dumps reduce surface rehabilitation requirements, lowering closure costs.

of improved waste management strategies. The main objectives of this study are:

1. Evaluation of operational challenges associated with inner dumping of waste material in open pit mining and their impacts on mining operations and its cost.

2. Impact of inner dumping on mine planning and design in relation with safety, efficiency and long-term sustainability.

3. To explore the innovative practices for efficient inner dumping of waste rock

Materials and Methods

Study Area

The Sindh Coal fields located in Thar-Parkar district of Sindh named as the world's 7^{th} largest coal projects, are contributing well to the power sectors of Sindh province of Pakistan. These coal fields are divided into different blocks. B-1 is expanded at longitudinal 67°¬44' towards east and latitudinal 23° 42' towards north. Notably, this region lacks surface water bodies, and the climate is characterized by significant temperature variations. These environmental characteristics significantly influence the stability and dynamics of the open-pit coal mine, warranting careful consideration in risk assessment and management strategies.

Figure 1 shows the Thar Coal Block-1 region, highlighting roads, villages, airports, and planned infrastructure. The red blocks represent mining and power facilities, while the blue area indicates water bodies or drainage. It provides an overview of connectivity and development in the coalfield area. In the Thar coal fields of Pakistan, a huge Coal Mine named as TCB-1 boasts a designed production capacity of 780000 tons/y.

Layers and bedding plans are divided into three main parts: Sandy layer (I), Soft, rocky layers (II) and Soft, rocky layer (III). The Thar coalfield itself constitutes an extensive and gradual syncline oriented along the NNE direction, with mild layer occurrences angle of Dip of approximately 2°.

Fig. 1 Block-1 Open pit mining field photograph.

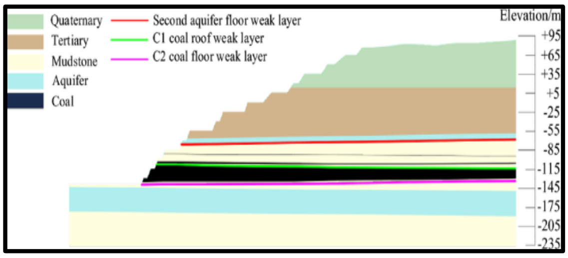

Fig. 2 Geological settings at B1.

Results and Discussion

Consolidation of waste materials in-site mine, helps to minimize overall carbon footprint of mine, thus, also impacts the operational costs. On the other hand, it can significantly, impact the mining operation if not taken seriously. Challenges to inner dumping are as follows.

Impact on Aquifer

Mining activities can significantly impact aquifers by contaminating groundwater with pollutants leached from waste materials. This contamination poses risks to drinking water, agriculture, and industrial uses, affecting both local communities and ecosystems downstream. Managing mining waste effectively through measures like liners and regular groundwater monitoring is crucial to prevent contamination and mitigate environmental harm. Advances in waste management and monitoring technologies are essential for sustainable mining practices that safeguard aquifers and ensure long-term environmental stewardship.

Surface Water Pollution

During periods of heavy rainfall, run-off from inner dumps can transport pollutants such as sediments, heavy metals, and chemicals into nearby rivers, streams, and lakes. This run-off can lead to significant degradation of water quality, impacting aquatic ecosystems and the organisms that depend on them. Sediments can smother fish habitats, clog gills and covering spawning grounds, and reducing light penetration, which adversely affects photosynthetic aquatic plants and algae. Heavy metals and chemicals pose severe toxicological threats to aquatic life.

These pollutants can cause physiological and behavioural changes in fish and invertebrates, and bioaccumulation in the food chain can lead to higher concentrations of toxins in predators, including humans who consume contaminated fish. Contaminated water poses a risk to human health if used for drinking, recreation, or irrigation, potentially leading to serious health conditions such as neurological damage and cancer.

Soil Deterioration

The operation of heavy machinery during inner dumping in open-pit and open-cast mining exerts significant pressure on the soil, causing compaction that drastically reduces its porosity and permeability. This compaction limits the ability of roots to penetrate the soil, stifling plant growth and reducing water infiltration. Consequently, it becomes challenging for vegetation to re-establish, disrupting the natural regeneration processes of the ecosystem.

This impediment to root growth and water movement also exacerbates erosion, as compacted soil is less able to absorb and retain rainfall, leading to increased surface run-off. The degraded soil can remain unproductive for extended periods, making it difficult to return the area to its natural state. Long-term soil degradation impacts not only plant growth but also the broader ecological balance, affecting wildlife habitats and water quality.

Air Quality Concerns

In open-pit and open-cast mining operations, inner dumping activities generate substantial dust and particulate matter, which wind can easily disperse, leading to diminished air quality around the mining site. This airborne dust poses significant health risks to both workers and nearby residents, contributing to respiratory problems, cardiovascular issues, and other health concerns. Moreover, mining waste often contains volatile organic compounds (VOCs) and other hazardous substances that can be released into the atmosphere during dumping and storage.

Operational Disadvantages

The frequent movement of heavy machinery within restricted spaces accelerates wear and tear, leading to higher maintenance expenses and shorter equipment lifespans. Mining operations face several operational disadvantages related to inner dumping, mainly due to limited space for waste, interference with mining activities, and increased operational costs.

Managing waste within a confined area significantly raises operational costs due to the need for precise handling and transportation solutions, which can be more costly. The frequent movement of heavy machinery within restricted spaces accelerates wear and tear, leading to higher maintenance expenses and shorter equipment life.

Economic Disadvantages

Mining operations face significant economic disadvantages due to the complexities of inner dumping, including reduced efficiency, long-term liability, and increased rehabilitation costs. Managing inner dumps decreases operational efficiency, impacting productivity and profitability. Inefficiencies in waste management increase costs for materials handling, transportation, and equipment maintenance, potentially leading to financial instability.

The risk of environmental contamination from inner dumps poses long-term liabilities, including substantial costs for remediation, clean-up, and legal compliance. Thus, the economic disadvantages of inner dumping highlight the need for strategic planning, efficient waste management practices, and sustainable rehabilitation approaches to mitigate financial risks and ensure the long-term viability of mining projects.

Safety Disadvantages

Mining operations face significant safety challenges related to inner dumping, primarily due to slope stability issues, fire hazards, and increased accident risk. The added weight of waste materials can destabilize pit walls, increasing the risk of landslides and slope failures, which endanger workers and equipment. To prevent serious incidents such as injuries, fatalities, equipment damage, and operational disruptions, continuous monitoring and mitigation measures like slope reinforcement and drainage control are crucial. A proactive approach to monitoring, prevention, and response is required to safeguard workers' well-being and maintain operational integrity in mining projects.

The Figure 3 shows the simulated results of cost comparison of inner dumping with external dumping. This graph mainly compares the volume of waste in both cases. This graph is drawn between waste volume on x-axis and cumulative disposal cost on y-axis. External dumping shows steep rise in cost as the volumes of waste increases.

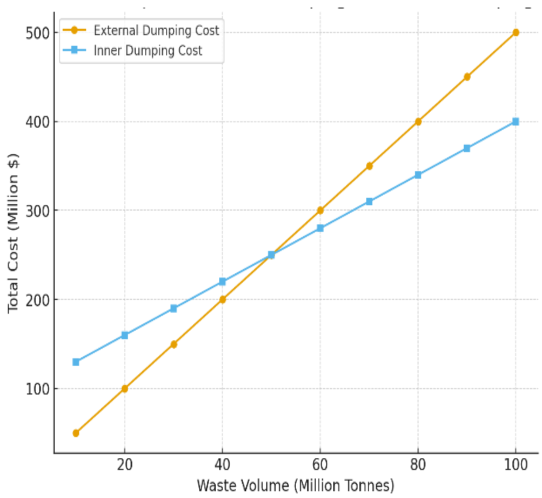

Fig. 3 Cost-comparison of inner-dumping and external dumping at Block B1.

This is because of the higher cost on fuelling, longer distances, equipment wear and maintenance, and the external population rehabilitation. However, on the other side, the inner dumping line increases more gradually.

Fuelling cost is lower in the case of inner dumping, as well as, minimal external land disturbance, with low waste volumes. But inner dumping also promotes confined places, geotechnical, and mine operational challenges.

Conclusion

Inner dumping can reduce the external footprint of mining operations but poses environmental risks like contamination and habitat disruption. Effective management strategies are necessary to mitigate these impacts. Integrating inner dumping with reclamation efforts enhances environmental sustainability by restoring mined areas.

Optimizes space use within the mining site, but meticulous planning is required to avoid obstructing valuable ore access and ensure slope stability. Reduces the need for external dump sites but can increase costs for geotechnical stabilization and waste handling. Evaluating economic viability involves balancing savings with the costs of managing stability and operational risks. Added weight from inner dumping can compromise pit wall stability, posing safety hazards.

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