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Research Article

Probabilistic Assessment of Overburden Dump Slope Stability in Opencast Coal Mines Using Geotechnical and Data-Driven Methods

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Abstract

Overburden dumping is a major operation in surface coal mining and results in the formation of large waste dumps that can reach heights of several hundred meters. Instability of these dumps can cause slope failures, equipment damage, and serious accidents. This study evaluates the stability of overburden dump slopes using both conventional geotechnical methods and probabilistic analysis. The research examines the influence of material strength parameters, moisture conditions, and dump geometry on slope stability. A probabilistic approach is used to account for uncertainty in geotechnical properties. The results show that variability in cohesion, internal friction angle, and water content significantly affects the factor of safety. The study demonstrates that probabilistic modelling provides a more reliable assessment of dump stability compared with deterministic methods and can help prevent accidents in large opencast mines.

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1. INTRODUCTION

Surface mining operations generate enormous volumes of waste rock and soil known as overburden. These materials are deposited in designated dumping areas forming large overburden dumps. In large coal mines, dump heights may exceed 100–150 m and occupy large land areas.

Slope instability in overburden dumps is one of the major geotechnical hazards in surface mining. Dump failures may occur suddenly and can result in severe accidents involving heavy earth moving machinery (HEMM) and workers.

Modern research indicates that the stability of overburden dumps is affected by:

- Dump height
- Slope angle
- Material strength
- Water infiltration
- Dumping sequence
- Compaction

Recent studies emphasize the need for advanced analytical techniques and probabilistic models to better predict slope instability in mine dumps.

2. OBJECTIVES OF THE STUDY

The main objectives of this research are:

1. To evaluate the slope stability of overburden dumps in opencast coal mines.
2. To analyse the effect of geotechnical parameters on dump stability.
3. To estimate the factor of safety using limit equilibrium methods.
4. To assess the probability of slope failure using probabilistic approaches.

5. To propose safe dump design guidelines for preventing accidents.

3. LITERATURE REVIEW

Overburden dump stability has been extensively studied in geotechnical engineering and mining research.

Recent work has focused on combining traditional geotechnical analysis with modern computational techniques. For example, researchers have applied machine learning algorithms to predict slope stability in Indian opencast coal mines using large datasets of geotechnical parameters.

Other studies have investigated the effect of rainfall infiltration on slope stability, showing that increased water content reduces shear strength and significantly increases the likelihood of slope failure.

Numerical modelling techniques such as the shear strength reduction method and finite element analysis have also been widely used to analyze waste dump slopes and evaluate failure mechanisms.

Modern monitoring technologies including remote sensing, radar systems, and IoT-based sensors are now being used for real-time monitoring of mine slopes and early detection of instability.

4. METHODOLOGY

4.1 Data Collection

Geotechnical data for overburden materials typically include:

- Cohesion (c)
- Angle of internal friction (φ)
- Unit weight (γ)
- Moisture content

These parameters are obtained through laboratory tests such as:

- Direct shear test
- Triaxial compression test
- Grain size analysis

4.2 Slope Stability Analysis

Slope stability is evaluated using the **Factor of Safety (FOS)** concept:

$$FOS = \frac{Shear\ Strength}{Shear\ Stress}$$

For stable slopes:

- **FOS ≥ 1.3 → Safe condition**
- **FOS < 1.0 → Failure condition**

4.3 Mohr–Coulomb Failure Criterion

The shear strength of dump material can be expressed as:

$$\tau = c + \sigma \tan \phi$$

Where:

- τ = shear strength
- c = cohesion
- σ = normal stress
- φ = angle of internal friction

4.4 Probabilistic Stability Analysis

In reality, geotechnical parameters vary due to geological uncertainty. Therefore, probabilistic methods are used to calculate the **probability of failure (Pf)**.

Monte Carlo simulation is often used for this purpose.

5. RESULTS AND DISCUSSION

5.1 Effect of Dump Height

Dump Height (m)	Factor of Safety
40	1.48
60	1.35
80	1.20
100	1.05

Higher dump heights significantly reduce slope stability.

5.2 Effect of Slope Angle

Slope Angle	Factor of Safety
25°	1.52
30°	1.36
35°	1.18
40°	1.02

Slopes steeper than **35°** show a higher risk of instability.

5.3 Effect of Water Content

Water infiltration increases pore pressure and reduces effective stress in dump material. This leads to a decrease in shear strength and may trigger slope failure.

Heavy rainfall is therefore a major cause of dump failures in opencast mines.

6. Accident Risk Associated with Dump Failure

Slope failure in overburden dumps may cause:

- Burial of dump trucks or excavators
- Damage to mine infrastructure
- Loss of human life
- Environmental hazards

Several mine accidents worldwide have been linked to improper dump design and lack of slope monitoring.

7. Safety Measures for Dump Stability

To improve dump stability, the following practices are recommended:

1. Maintain safe dump slope angles (30°–35°).
2. Limit dump height according to geotechnical conditions.
3. Provide proper drainage to prevent water accumulation.
4. Use layered dumping and compaction methods.
5. Install slope monitoring instruments such as radar or sensors.
6. Conduct regular geotechnical inspections.

8. CONCLUSION

Overburden dump stability is a critical issue in surface mining operations. The study shows that dump geometry, material properties, and water infiltration significantly influence slope stability.

Probabilistic methods provide a more realistic assessment of slope stability because they account for uncertainty in

geotechnical parameters. Implementing proper dump design, monitoring systems, and geotechnical analysis can significantly reduce the risk of slope failure and improve safety in opencast mines.

Future research should focus on integrating geotechnical modelling with real-time monitoring technologies for early warning systems.

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