Instability of topsoil benches of a pit caused by dumping of waste rock outside an opencast coal mine

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Abstract

One of the consequences of large-scale opencast mining for coal is the disposal of an enormous volume of overburden material that needs to be removed. With the enlargement of opencast mines and associated high stripping ratios, the volume of overburden extraction is rising. Overburden from the initial mine cut has to be necessarily dumped outside the mining area until enough void is created inside the mine for back-filling operations. The quantity of overburden placed outside the mining area normally varies from 10% to 30% of the total overburden removal. The stability of these dumps placed outside the mining area is of prime importance from the point of view of smooth operations of the mines and safety of persons in and around the dumping area. Owing to increasing pressure on land use, mine operators do not have any other option other than to place the waste dumps very near to the surface edge of the pit, which may lead to failure of the topsoil benches of the working pit. This study identified major controlling parameters that influence a stable but economic combination of height and slope angle of external dumps located close to the edge of an open coal pit.

Keywords

slope stability, circular failure, opencast mining, shear strength parameters, overburden dump

Introduction

In India, some 45% of total opencast coal production is by dragline-operated mining, which is considered the most efficient way of winning coal for opencast mines linked to power plants. In dragline-operated opencast mines, the overburden comprises both dragline dump and shovel-dumper dump. The dragline dump comes from parting between the bottom-most seam and just above to bottom-most seam; the shovel-dump material originates comes from parting between intermediate seams and the top overburden above the upper seams. This complex process of dump formation by the combination of dragline and shovel-dumper creates difficulty in positioning of the shovel-dumper dump with respect to the dragline dump due to following reasons:

- ➤ Dragline dump is often of low cohesive strength and is placed without compaction. The re-handled dump material is allowed to pile up at its natural angle of repose, i.e., at limiting equilibrium.
- ➤ If the shovel-dumper material is dumped just above fresh dragline dump that is not compacted and is standing at an factor of safety (FoS) of 1.00–1.05, this will lead to failure of both dragline and shovel-dumper dumps.
- ➤ Dumping the shovel-dumper contents away from fresh dragline dump allows sufficient time for consolidation and development of cohesion and angle of internal friction within dragline dump mass, but will result in a substantial decrease in space for dumping.
- ➤ A reduction of space for dumping will lead to increase in height of both internal shovel-dumper and external dumps, thereby endangering the dump stabilities.
- ➤ The position of the shovel-dumper dump with respect to the toe of the fresh dragline dump is therefore a difficult decision for mine operators. This motivated an extensive study of this topic.

In opencast mining, the coal is mined after removing the overburden, which is placed either outside the open-pit area, known as external dumping, or in the void after de-coaling, i.e., within the open-pit area, known as internal dumping. Attempts are made to minimize external dumping to reduce the land use; however, the quantity of material to be placed as external or internal dumps depends on following geo-mining criteria (Sengupta and Roy, 2015; Zaitseva and Zaitsev, 2009):

- ➤ In case of multi-seam occurrences, especially in the Damodar Valley coalfield near Jharia and Raniganj (India), internal dumping over the de-coaled area of the upper seams will sterilize opencast mining of the lower seams. In such cases, it should be made certain that lower seams will not be workable in future by opencast methods. If there is a possibility of later opencast working of the lower seams, then the overburden removed from the top seams has to be placed as external dumps.

- In case of steep seam occurrence, simultaneous mine working and back-filling with the help of draglines is difficult. In such cases, back-filling may be performed in adjoining voids, if these exist; otherwise, overburden removal has to be placed as external dumps
- The location of external dumps requires selection of suitable sites. External dumping may be avoided, if possible, in the following site conditions, shown in Figure 1: (i) dumping over alluvium or soft-soil strata very close to the open-pit edge, (ii) dumping over a fault plane (Pit Slope Manual, 1976) that is exposed and dipping towards the quarry batter.

External dumping can be placed either close to or away from the pit crest. The following factors are considered in case of external dumping close to the pit crest:

- External dumps are normally placed close to the open-pit area to reduce the traverse distance of the overburden haul trucks, which in turn reduces the total complement of trucks operating in the mine;
- It is environmentally harmful to move overburden materials away from the pit area;
- Mining and dumping are in close proximity to the pit, which can facilitate management;
- Acquisition of large areas of land is required, with the concurrent problem of depletion of forest area.

Considering these factors, mine operators are often forced to place waste materials very near the edge of the working pit, which may lead to failure of the top benches of the pit batter due to surcharge loading of the external dump material. Determination of the optimum distance of the external dump from the edge of the nearest working-pit crest is necessary for both safety and land use management considerations.

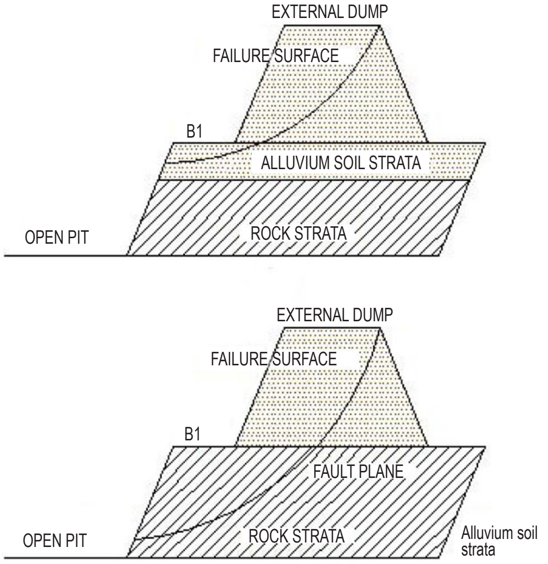
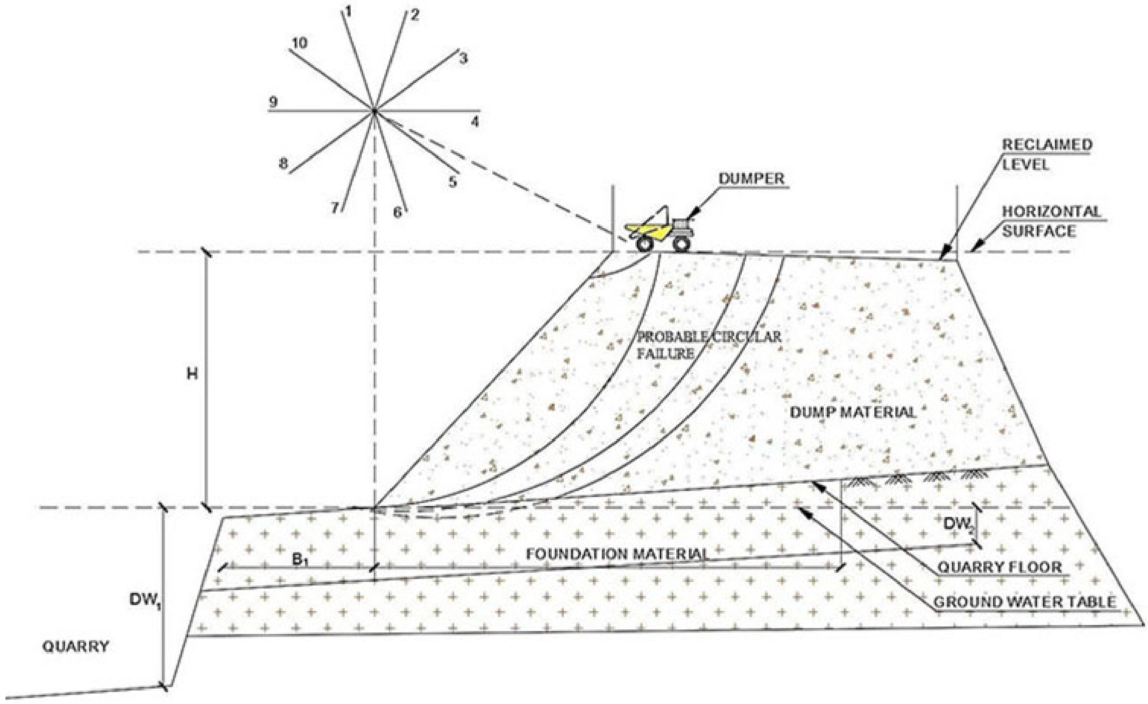


Figure 1—Circular slip surfaces through weak dump and foundation material

Objective of study

The main objective of this study was to elucidate, using a computerized model, the influence of distance (B_1) between the toe of the dump and the nearest surface edge of the open pit on the slope geometry of an external dump, i.e., slope and height of the dump (Figure 2) (Pit Slope Manual, 1976; Roy, 1998), depending on various geotechnical parameters (Roy, 2008).

Here, some parameters were kept constant and others were considered variable to show their influence on distance B_1. Parameters that were kept constant are as follows (Sengupta and Roy, 2015; Sengupta et al., 2016):



B_1: distance of toe of external dump from surface edge of the open pit crest; H: height of dump; DW_2: depth of water table below external dump; DW_1: height of accumulated water table within quarry

Figure 2—Probable failure surfaces in overburden benches

- ➤ Cohesion and angle of internal friction of dump material (C_2, f_2);
- ➤ Unit weight of dump material (g_2);
- ➤ Ground acceleration due to blasting (A_g) (Indian Standard 1893 (Part 1), 2002);
- ➤ Capacity of dumper plying above dump-capacity and its surcharge load on the failure surface, shown in Figure 2.

The parameters that were considered variable are as follows (Sengupta and Roy, 2015; Sengupta et al., 2016) (Figures 2 and 3):

- ➤ Distance of toe of external dump from the edge of the open-pit crest (B_1);
- ➤ Height (H) and slope angle (b) of dump;
- ➤ Cohesion and angle of internal friction of foundation material (C_1, f_1);
  Unit weight of foundation material (g_1);
  Depth of water table below external dump (DW_2);
  Height of accumulated water table within the open pit (DW_1).

Back-analysis methodology

The following steps were employed for the back analysis (Roy et al., 2013):

1st step - FoS of the first trial surface was determined by the Fellenius method (Sengupta and Roy, 2015) with assumed values of cohesion and angle of internal friction of the dump material (close to the laboratory-determined value) and other geo-engineering parameters stated above.

2nd step - An iterative method was carried out to determine the most critical failure mode and corresponding absolute minimum FoS using the Fellenius method (considering that the FoS determined by Fellenius method is not absolute and can be underestimated).

3rd step - The FoS was modified using Bishop's Simplified method (Sengupta and Roy, 2015), which produced results that were more or less equivalent to those obtained by other complex methods, such as those of Janbu, Morgenstern–Price, and Spencer.

4th step - The above method was repeated until the most favourable combination of cohesion and angle of internal friction of dump mass was obtained for which the FoS was equal to 1.0.

To determine the site-specific shear strength parameters; namely, cohesion (C_1) and angle of internal friction ($\phi 1$) (despite using laboratory-obtained values, due to the difficulty in accurately simulating site conditions), back analyses were conducted for overburden slopes along problematic sections in the study. These were slopes that had failed and/or were considered to be standing at limiting equilibrium, i.e., with an FoS equal to 1, or were on the verge of failure. The most frequently used approaches for assessing slope stability and constructing engineered slopes are limit equilibrium (LE) methods (Oh and Lu, 2015). One of the most accurate methods for determining the shear strength of slope material at the moment of failure is to conduct an LE back analysis of a collapsed slope, i.e., circular slope failure (Sancio, 1981; Topal and Akin, 2009; US Army Corps, 2003). For design, the shear strength parameters acquired by back analysis of slopes are recognized as being more consistent than those obtained by laboratory or in situ testing (Popescu and Schaefer, 2016). All feasible representative cohesive interpretations (nearer to the laboratory-defined value) of dump material are analysed and values of the angle of internal friction of the dump mass are achieved for which the FoS is about 1.0 are compared by stability analysis. Similarly, all probable representative values of angle of internal friction (nearer to the laboratory-defined value) are analysed and similar cohesive values of the dump are obtained for which the FoS is about 1.0 (Zhang et al., 2010).

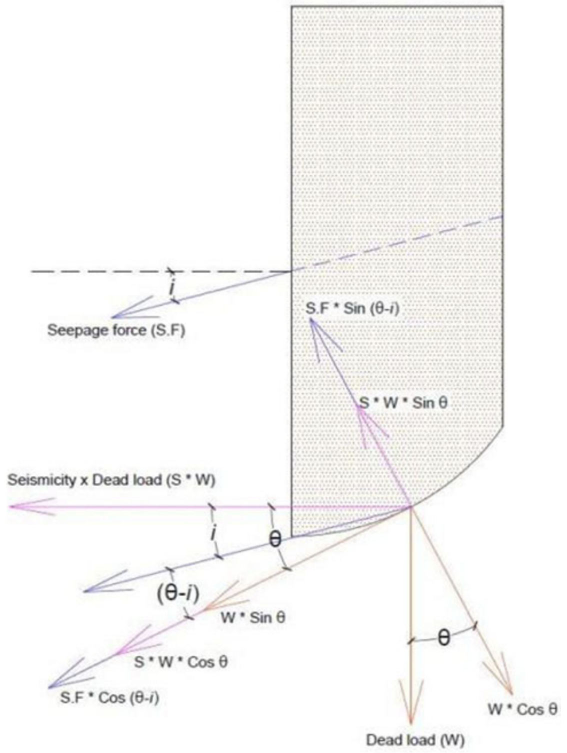


Figure 3—Forces acting on a slice (Golder and Roy, 2022)

Back analysis was performed for failed overburden slopes and those considered to be standing at limiting equilibrium along problematic sections in the study area to identify the site-specific shear strength parameters; namely, C_1 and $\phi 1$. The back-analysis results are tabulated in Table I.

Analysis, results, and discussion

Fellenius method used to calculate the safety factor

To determine FoS using the Fellenius method for a circular mode of failure, a trial surface was considered for an assumed part of the overburden slope (Figure 2). This was divided into a number of slices as necessary for subsequent calculations by randomly picking the centre for the iteration technique. The various forces acting on each slice are (Figures 3 and 4):

a) Force caused by the dead load, i.e., self-weight;
b) Effect of seismicity;
c) Blasting in the open pit for mining operations generates forces on the slice and, as a result, on the slope;
d) Upward thrust of water on each slice due to the presence of a water table within the overburden slope;
e) Water seepage force on each slice caused by water flowing through the overburden and highwall slope.

$$\text{Disturbing force} = [W \sin\theta + SW \cos\theta + SF \cos(i - \theta)], \qquad [1]$$

where S is the seismic co-efficient.

$$\text{Frictional force} = [W \cos\theta + SF \sin(i - \theta) - SW \sin\theta] \times \tan\phi \qquad [2]$$

Table I

Back-analysis results

Slope no.	Cohesion C (kN/m^2)	Angle of internal friction (ϕ)	Co-ordinates of failure path	Disturbing force (kN)	Frictional force (kN)	Cohesive force (kN)	FOS (FM)*	FOS (BM)*
1	70	34	$X_1 = 18.33$ $Y_1 = 115$ $XX_1 = -19.33$	573 672	440 078	148 292	1.026	1.325
2	74	36	$X_1 = 20$ $Y_1 = 130$ $XX_1 = -10$	651 891	491 796	206 514	1.071	1.431
3	81	38	$X_1 = 15$ $Y_1 = 110$ $XX_1 = -5$	501 961	441 796	166 574	1.350	1.629

*FM – Fellenius method and BM – Bishop's Simplified Method

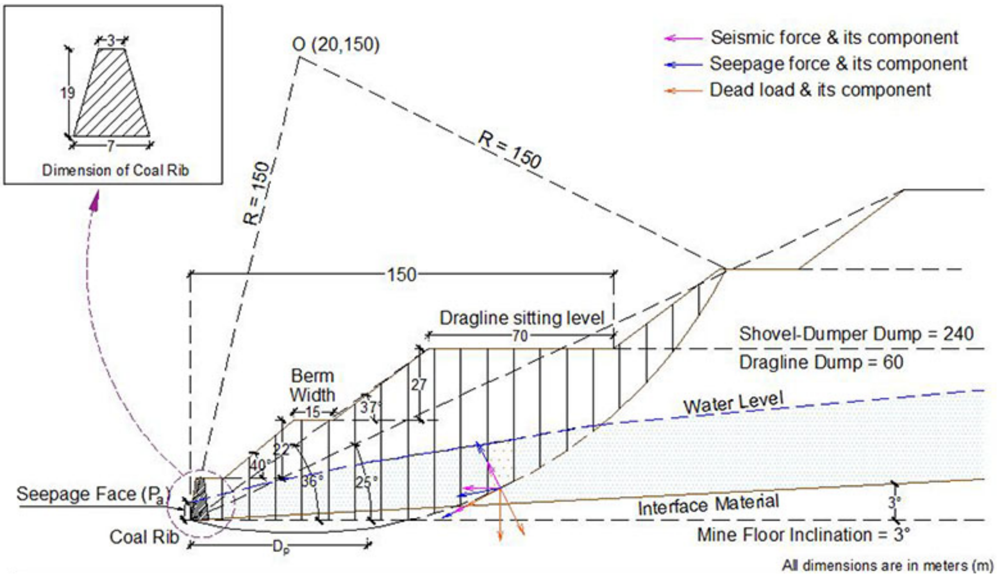


Figure 4—Jayant opencast project (ocp) showing circular plane failure surface (Golder and Roy, 2022)

$$\text{Cohesive force} = (\text{radius of failure mode}) \times (\text{Z in radian}) \times (\text{cohesion of dump mass}) \times \text{width of the slice} \quad [3]$$

$$\text{Resisting force} = \text{Frictional force} + \text{cohesive force} \quad [4]$$

$$FS_1 = \frac{\text{Resisting force}}{\text{Disturbing force}}. \quad [5]$$

FS_1 of the chosen trial surface was the ratio of cumulative resisting forces to cumulative disturbing forces.

Bishop's simplified method to determine factor of safety

The FoS (FS_1) calculated by the Fellenius method (Equation [5]) has some inaccuracy because inter-slice forces are ignored, Bishop's simplified method was used to obtain more precise findings using Equation [6:]

$$FS = (\text{frictional force} + \text{cohesive force}) / \{m \times (\text{disturbing force})\}, \quad [6]$$

where

$$m = \cos(90 - \theta)\left[1 + \frac{(\tan(90-\theta) \times \tan\phi)}{FS_1}\right] \quad [7]$$

{NOTE: $m < 1$; if $m > 1 \approx 1$}

Values obtained were as follows:

- FoS using Fellenius method = 1.182,
- 1st FoS using Bishop's Simplified method = 1.325,
- 2nd FoS using Bishop's Simplified method = 1.397.

After considering all the recommended factor of safety suggested by different agencies such as National Coal Board U.K, United States D'Appolonia consulting engineers, Mines branch Canada, and Stability of pit slopes and dumps by G.L. Fiesenko, Russia for surface mine slope design, a factor of safety of more than 1.30-1.35 is envisaged here for the design of coal mines in Indian conditions which considers maximum seismic acceleration.

The optimum combination of height and slope of dump corresponding to a stipulated FoS of 1.30–1.35 (Roy, 1998) was selected and compared with the FoS determined by Bishop's Simplified method. If the calculated FoS is less than 1.30, then a milder slope is to be considered to match the stipulated FoS; if the calculated FoS exceeds the stipulated range, then a steeper slope should be considered.

FoS considering seismicity and seepage force by Fellenius method is 1.182; that by Bishop's Simplified method is 1.325.

For a dump on weak foundations, there is a steady increase in height or steepening of slope angle for an increase in the value of B_1 (Figure 5); however, this is only true up to a particular value of B_1, which differs for different combinations of input parameters.

Figure 5 shows no increase in stable height of dump for change in value of B_1 from 5 m to 10 m when the angle of internal friction of the foundation material (f_1) is ≥ 25°; whereas there is a steady increase in the stable height of the dump (Table III) for a change in value of B_1 from 0 to 10 m when $f_1 = 20°$.

With increase in shear strength of foundation materials (C_1, f_1), there is a steady increase in the stable height of the dump for a particular value of slope angle and particular value of B_h (Figures 5 and 6) (Sengupta et al., 2014).

For Figure 2, variations of slope geometry with different values of angle of internal friction of foundation material (f_1) are presented in Table III.

In Table II, variations of slope geometry with different values of cohesion of foundation material (C_1) are presented in Tables IV and V.

The angle of internal friction of the foundation is already below 20°, so the external dump is unsafe within 10 m of the pit crest when cohesion of the foundation is less than or equal to 30 kN/m2 (Figure 6).

Table II

Variation of slope geometry for different values of angle of internal friction (Φ_1) of foundation material and B_1 = 5 m distance between toe of external dump and surface edge of the pit slope batter with seepage

Angle of internal friction (Φ1 (°)	Maximum stable angle (β) (°)	Maximum stable height (H) of dump (m)	FOS
20	27	60	1.391
25	32	75	1.253
30	34	70	1.167
35	35	69	1.078

Table III

Variation of height of dump with B_1 = 5 m, slope angle (b) = 25°, and FOS = 1.325

Angle of internal friction (f_1) (°)	20	25	30	35
Height of dump (H) (m)	30	60	90	90

The effect of unit weight of foundation material (g_1) is not significant in comparison with cohesion (C_1) and angle of internal friction (f_1) (Figure 6).

Comparing Figures 5–7 with Figures 8–10, it can be concluded that there is a steady decrease in the stable height for seepage of ground water through the foundation of the dump, as shown in

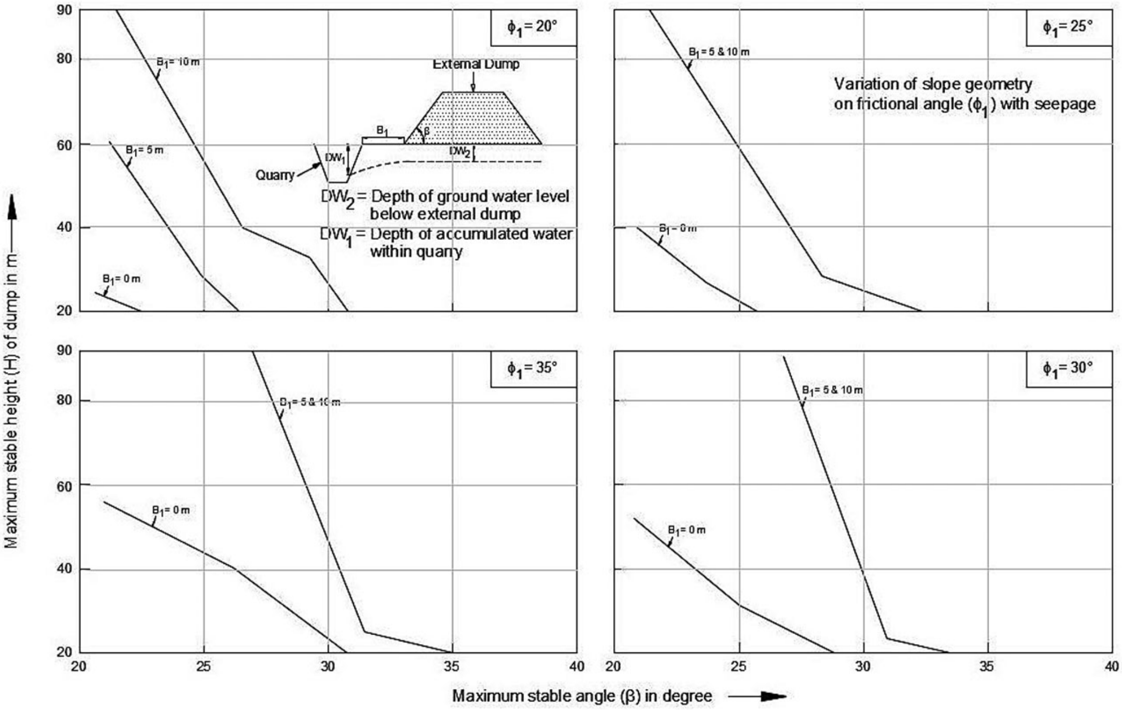


Figure 5—Influence of face angle of external dump on its stable height in high-risk zone (FoS: 1.30–1.35) for different values of angle of internal friction (Φ_1) of foundation material and B_1 distance between toe of external dump and surface edge of the pit slope batter. $\Phi_2 = 40°$, $C_2 = 15$ kN/m², $C_1 = 35$ kN/m², $DW_2 = -2$ m, $DW_1 = -20$ m, Unit weight of foundation material (Υ_1) = 19 kN/m³, Unit weight of dump material (Υ_2) = 21 kN/m³, $A_g = 0$, capacity = 50 t

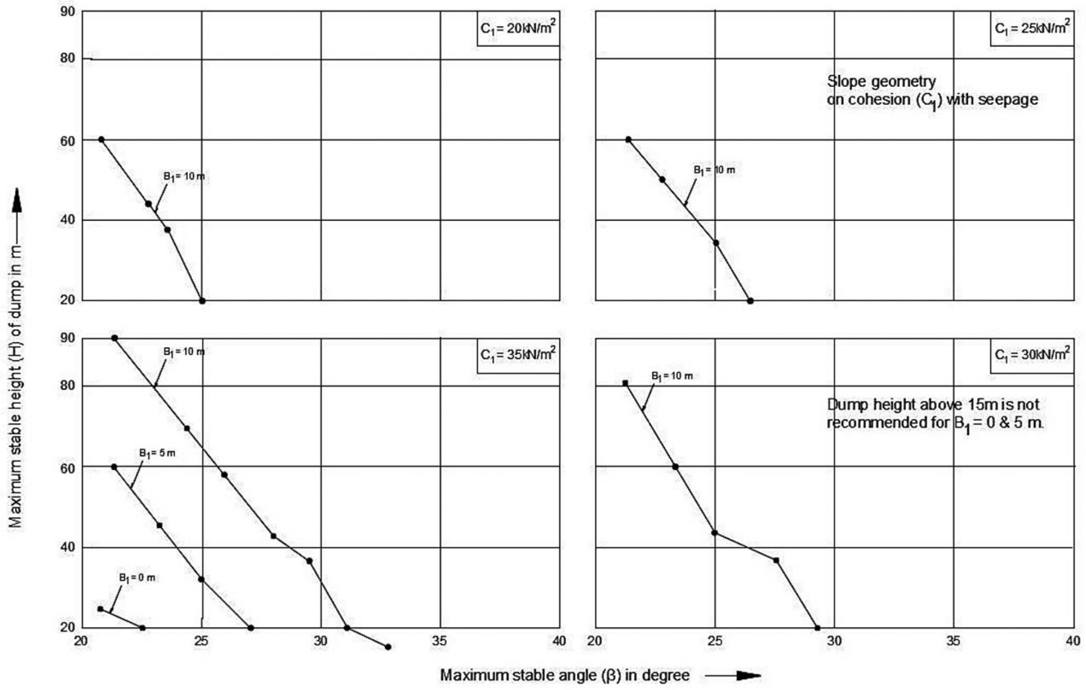


Figure 6—Influence of face angle of external dump on its stable height in high-risk zone (FoS: 1.30–1.35) for different values of cohesion of foundation material (C_1) and B_1 distance between toe of external dump and surface edge of pit crest batter. $\Phi_2 = 40^\circ$, $\Phi_1 = 20^\circ$, $C_2 = 15$ kN/m2, $DW_2 = -2$ m, $DW_1 = -20$ m, $\Upsilon_1 = 19$ kN/m3, $\Upsilon_2 = 21$ kN/m3, Ag = 0, capacity = 50 t

Table IV

Variation of slope geometry for different values of cohesion of foundation material (C_1) of foundation material and B_1 = 10 m distance between toe of external dump and surface edge of the pit slope batter with seepage

Cohesion (C_1) kN/m2	Maximum stable angle (β) (°)	Maximum stable height (H) of dump (m)	FOS
20	25	60	1.325
25	27	60	1.214
30	29	79	1.295
35	31	80	1.394

Table V

Variation of height of dump B_1 = 10 m, slope angle (b) = 25°, and FOS = 1.261

Cohesion of foundation material (C_1) (kN/m2)	20	25	30	35
Height of dump (H) (m)	20	35	40	55

Table VI. Depth of the water table (DW_2) is −2m in Figures 5–7), i.e., there is seepage of ground water through the foundation of the dump; whereas DW_2 is − 20 m in Figures 8–10), i.e., there is no seepage of ground water through the foundation. Hence, there is a decrease in safe height of dump due to seepage through the foundation of the dump in comparison with no seepage.

Table VI

Comparison of heights of dump with seepage condition and without seepage condition B_1 = 5 m, slope angle (b) = 21°, angle of internal friction of foundation material (f_1) = 20°, and FOS = 1.351

	With seepage	With seepage
Depth of water table (DW_2) (m)	−2	−20
Depth of water table (DW_1) (m)	−20	−20
Height of dump (H) (m)		70

Precautionary measures

In addition to maintaining the recommended geo-engineering parameters of shear parameters (C and ϕ) of dump and foundation material, dynamic forces (seismicity of the area and vibration due to blasting), hydrogeological parameters (upward thrust and seepage force), and mine floor inclination, the following measures are recommended:

1. Floor gradient of the mine should be maintained to ensure consistent natural gravitational flow of water towards the sump, thereby ensuring minimum accumulation of water in the de-coaled floor of the pit.
2. If a coal rib is left against the toe of the dump, its dimension should not exceed the recommendations of 7–7.5 m at the base and 1 m at the roof with full coal-seam thickness of 16–18 m and 4 m at the roof and 7 m at the base with half coal-seam thickness of 9–10 m (Sharma and Roy, 2015) (Figure 11).
3. No low-bearing capacity soil should be allowed to be dumped on the floor of the de-coaled area to form the base of the dump.

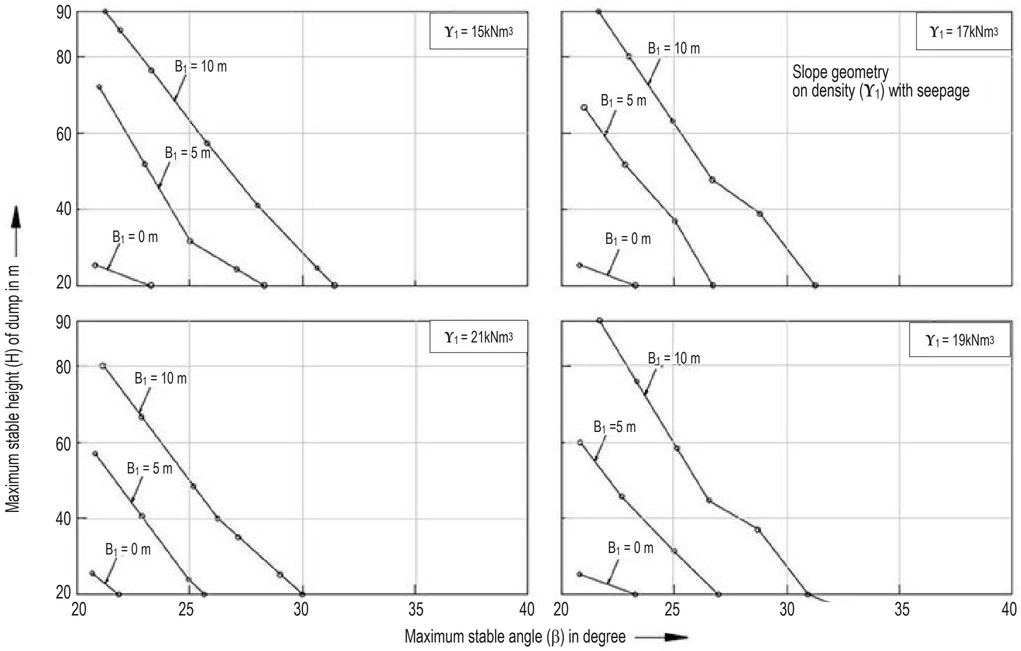


Figure 7—Influence of face angle of external dump on its stable height in high-risk zone (FoS: 1.30–1.35) for different values of unit weight of foundation material (Υ_1) and B_1 distance between toe of external dump and surface edge of pit crest batter. $\Phi_2 = 40^\circ$, $\Phi_1 = 20^\circ$, $C_2 = 15$ kN/m^2, $C_1 = 35$ kN/m^2, $DW_2 = -2$ m, $DW_1 = -20$ m, $\Upsilon_2 = 21$ kN/m^3, Ag = 0, capacity = 50 t

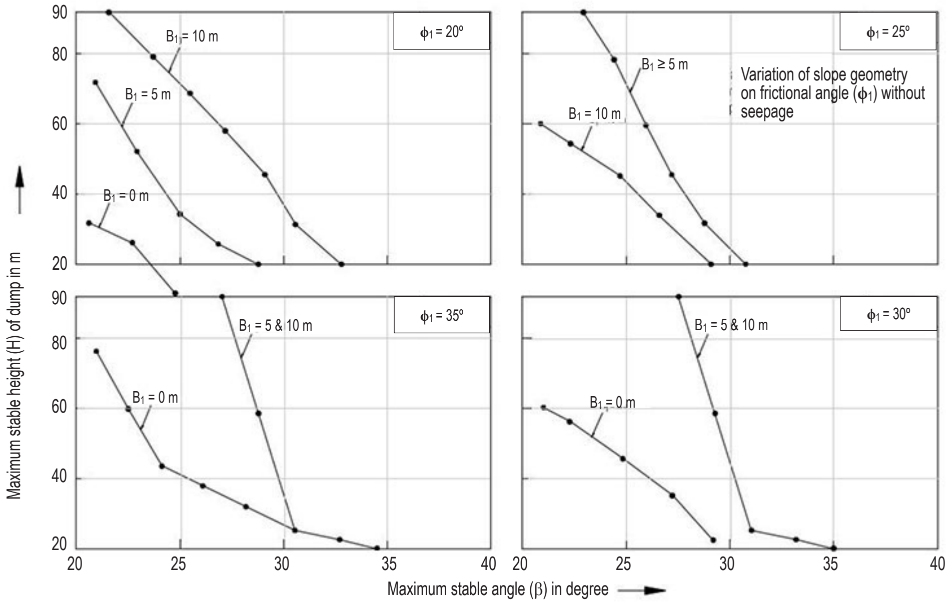


Figure 8—Influence of face angle of external dump on its stable height in high-risk zone (FoS: 1.30–1.35) for different values of angle of internal friction of foundation material (Φ_1) and B_1 distance between toe of external dump and surface edge of pit crest batter, without seepage through foundation of dump. $\Phi_1 = 20^\circ$, $C_2 = 15$ kN/m^2, $C_1 = 35$ kN/m^2, $DW_1 = -20$ m, $DW_2 = -20$ m, $\Upsilon_1 = 19$ kN/m^3, $\Upsilon_2 = 21$ kN/m^3, Ag = 0, capacity = 50 t

4. Topsoil should be separately dumped. as far as possible away from the site of active internal dumping.
5. The valley in the dragline dump may be filled up by dozing to the maximum possible volume of overburden.
6. The coal rib left at the toe of dump contributes little to the stability of the internal dump, but is prone to spontaneous heating and should be covered by dump material to the extent possible.
7. The interface layer, i.e., debris of coal dust, fragmented rock, and soil mixed with water, should be cleared as far as possible from the de-coaled floor before dumping by dragline.
8. The interface layer should be cleaned from areas where coal has been mined before being dumped by dragline (Singh et al., 2012). If possible, crushed overburden rock should be dropped in its place to cover the slushy ground at the dragline dump's base to increase the friction angle.
9. Minor blasting facilitates passage of water through the pit floor to the competent sandstone strata, thus preventing accumulation of water at the base of the dump.
10. The toe of the shovel dump should be formed at least 110–180 m away from the toe of the dragline dump to allow adequate time to stabilize before fresh dumping by the haul trucks.

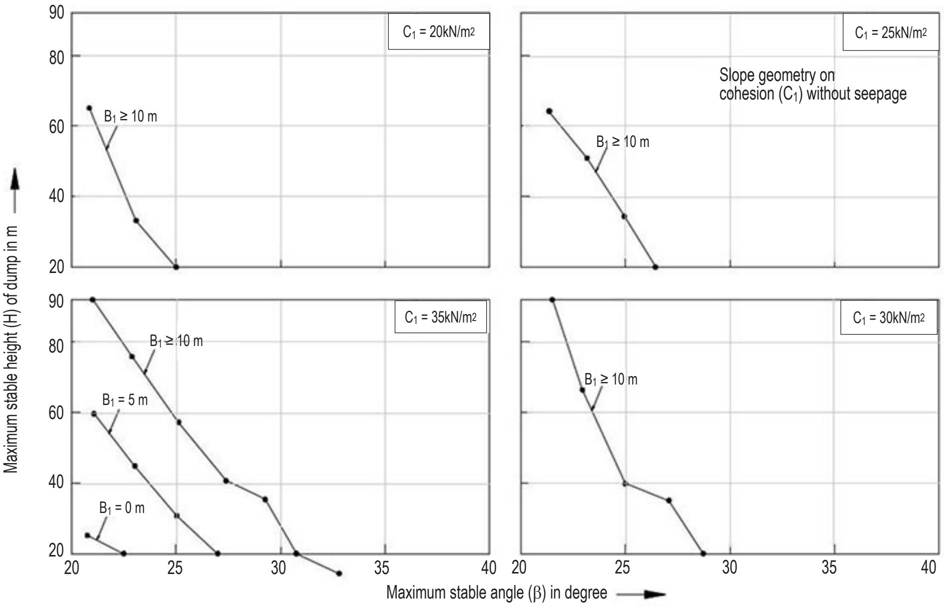


Figure 9—Influence of face angle of external dump on its stable height in high-risk zone (FoS: 1.30–1.35) for different values of cohesion of foundation material (C_1) and B_1 distance between toe of external dump and surface edge of pit-crest batter, without seepage through foundation of dump. $\Phi_1 = 20^o$, $\Phi_2 = 40^o$, $C_2 = 15\ kN/m^2$, $DW_1 = -20\ m$, $DW_2 = -20\ m$, $\Upsilon_1 = 19\ kN/m^3$, $\Upsilon_2 = 21\ kN/m^3$, Ag = 0, capacity = 50 t

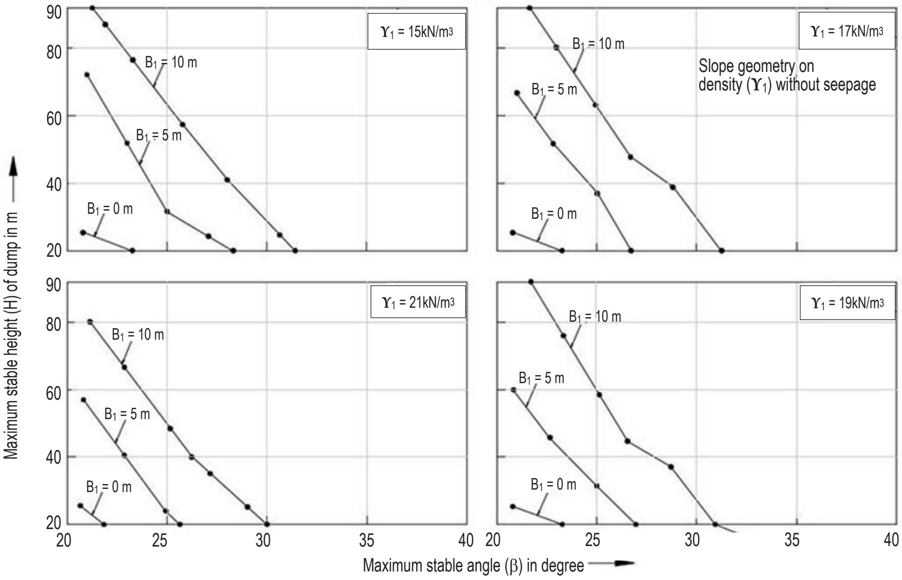


Figure 10—Influence of face angle of external dump on its stable height in high-risk zone (FoS: 1.30–1.35) for different values of unit weight of foundation material (Υ_1) and B_1 distance between toe of external dump and surface edge of pit crest batter, without seepage through foundation of dump. $\Phi_1 = 20^o$, $\Phi_2 = 40^o$, $C_1 = 35\ kN/m^2$, $C_2 = 15\ kN/m^2$, $DW_1 = -20\ m$, $DW_2 = -20\ m$, $\Upsilon_2 = 21\ kN/m^3$, Ag = 0, capacity = 50 t

Table VII

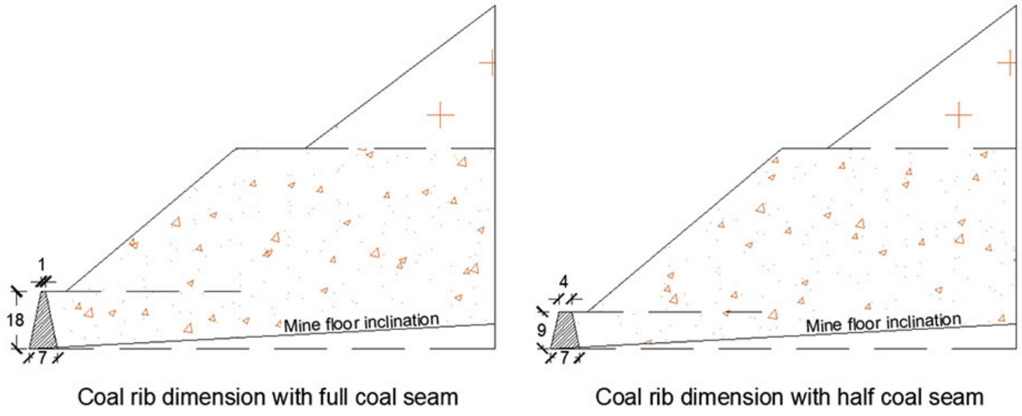
Variation of slope geometry for different values of angle of internal Friction ($\Phi 1$) of foundation material and $B_1 = 5$ m distance between toe of external dump and surface edge of the pit slope batter without seepage

Angle of internal friction ($\Phi 1$) (°)	Maximum stable angle (β) (°)	Maximum stable height (H) of dump (m)	FOS
20	27	70	1.373
25	31	60	1.246
30	35	58	1.171
35	35^o	58	1.069

Table VIII

Variation of slope geometry for different values of cohesion of foundation material (C_1) of foundation material and $B_1 = 10$ m distance between toe of external dump and surface edge of the pit slope batter without seepage

Cohesion (C_1) (kN/m^2)	Maximum stable angle (β) (°)	Maximum stable height (H) of dump (m)	FOS
20	25	69	1.324
25	26	65	1.220
30	28	60	1.289
35	31^o	58	1.389



Coal rib dimension with full coal seam

Coal rib dimension with half coal seam

Figure 11—Coal rib dimensions

Table IX

Variation of slope geometry for different values of unit weight of foundation material (Υ_1) of foundation material and B_1 = 5 m distance between toe of external dump and surface edge of the pit slope batter without seepage

Unit weight (Υ_1) (kN/m³)	Maximum stable angle (β) (°)	Maximum stable height (H) of dump (m)	FOS
15	29	73	1.312
17	28	69	1.285
19	27	60	1.197
21	26	58	1.102

11. A dump-monitoring cell may be established to monitor movements within the dump slopes.
12. Monitoring of toe, crest, slope angle below the dragline operating level, berm at the dragline level, and coal rib roof level should be regularly carried out and recorded (two to three times a week). In case of any movement in these areas, the working zone near the dragline dump should be declared a high-risk zone: mining activity should be stopped until further action in stabilizing the dump slope is taken.
13. Advanced slope-monitoring instruments, such as three-dimensional laser scanner or slope stability radar, are recommended for dragline dump monitoring.

Conclusion

This paper identifies major controlling parameters that influence a stable but economic combination of height and slope angle of external dumps located close to an open pit. Depending on parting thickness between the lowest coal seam and just above it and dragline capacity, these parameters can be applied for dragline dump design. An average water table height was considered.

A safe and economic distance of an external dump from the nearest open-pit batter depends on the total height of dragline and shovel dump; overall slope of dragline and shovel dump (as per the regulations (DGMS, 2017)); angle of internal friction, cohesion, and bulk unit weight of the dump material; angle of internal friction and cohesion of interface/foundation material, i.e., slushy material at the base of the dragline dump or foundation material; water table height inside the dragline dump; dump (mine) floor inclination; seismic zone of that particular area. Other than geometrical dimensions, i.e., height and slope angle, the influence of internal friction is found to be more pronounced than cohesion. Mine floor inclination is also a major influencing factor.

A dragline dump profile based on the combination of these factors can be designed by adjusting the berm width at the dragline operating level and that at coal rib roof level.

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