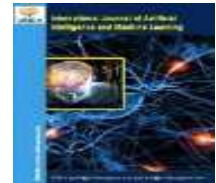




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Geotechnical Stability Analysis and Numerical Modelling for Optimization of Pit-to-Dump Distance Between an External Overburden Dump and an Opencast Coal Mine: A Case Study of the Godavari Valley Coalfields

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ABSTRACT

The safe placement of large overburden (OB) dumps adjacent to opencast coal-mine pit slopes is an important geotechnical and mine-planning challenge, particularly with the progressive deepening of opencast pits, increasing dump elevations, constrained dumping land and the need to maintain adequate stability margins. The present study evaluates the influence of dump surcharge, dump height and pit-to-dump setback distance on slope stability by integrating field investigation, laboratory geotechnical characterization, limit-equilibrium analysis (LEM) and three-dimensional distinct-element numerical modelling. Selected opencast coal mines in the Godavari Valley Coalfields of Singareni Collieries Company Limited (SCCL), Telangana as the case study. Twenty-seven representative OB samples from Mine A, II and III were characterized using sieve analysis, moisture-content determination, Standard Proctor compaction, specific gravity and direct shear testing. The measured cohesion ranged from 3 to 13.5 kPa and the internal friction angle from 26.9° to 52°, while specific gravity varied from 1.46 to 2.51. Bishop's Simplified Method and the Swedish slip-circle (Fellenius) approach were applied for dump heights of 30, 60, 90 and 120 m and pit-to-dump distances of 30, 60, 90 and 120 m. In addition, 3DEC sensitivity modelling examined overall slope angles of 25°–45°, pit-to-dump distances of 25–100 m, homogeneous and weak-layer foundation conditions, and a critical dump height of 120 m. The LEM results show a systematic increase in Factor of Safety (FoS) with increasing setback and a reduction in FoS with increasing dump height. Under the investigated dry-condition assumptions, pit-to-dump distances of 60, 90 and 120 m corresponded to FoS above 1.3 for dump heights up to 60, 90 and 120 m, respectively, across the three case mines. The numerical results independently demonstrate the sensitivity of the pit-dump system to slope geometry and weak geological horizons: for the homogeneous 25 m setback sequence, FoS decreased from 2.390 at 25° to 1.477 at 45°, whereas the mean weak-layer FoS increased from 1.242 at 25 m setback to 1.382 at 100 m. A regression relationship incorporating friction angle, cohesion, unit weight, dump height and setback distance achieved $R^2 = 0.742$. The integrated assessment indicates that pit-to-dump distance should be established as a mine-specific geotechnical design parameter governed jointly by dump geometry, material strength, foundation competence, slope configuration and geological structure rather than by adoption of a single universal distance.

Keywords: External overburden dump; pit-to-dump distance; setback distance; progressively deepening opencast mine; slope stability; Factor of Safety; dump surcharge; limit-equilibrium analysis; 3DEC; numerical modelling; weak geological layer; geotechnical characterization.

1 INTRODUCTION

Opencast coal mining generates substantial quantities of overburden (OB) material, which must be systematically excavated, transported, and accommodated in designated dumping areas. With progressive deepening and lateral advancement of open pits, the available space between the advancing pit crest and suitable dumping areas can become increasingly constrained. Placement of an external OB dump in the vicinity of a pit crest introduces an additional surcharge whose magnitude and spatial distribution influence the stress state and load-transfer mechanism within the dump, foundation and adjacent pit-slope system. The resulting stability response becomes particularly significant when dump height increases, the pit slope becomes steeper, or the foundation contains weak, fine-rich or structurally controlled zones.

From a mine-planning perspective, increasing the separation between the dump and pit crest generally reduces the surcharge influence on the critical slope region; however, excessive separation increases haulage distance, land requirement, cycle time, energy consumption and operating cost. The engineering problem is therefore to establish an optimum pit-to-dump distance that provides the required stability margin without imposing unnecessary constraints on the mine plan. This distance cannot be represented by geometry alone because slope stability is governed by the interaction of material shear strength, unit weight, slope height and angle, foundation competence, groundwater and pore-pressure conditions, geological discontinuities and the progressive loading history of the dump. [16, 17]

The present study focuses on Mine A, Mine AI and Mine AII of SCCL and integrates measured OB-material

properties with analytical and three-dimensional numerical stability assessment. The study objectives are to: (i) characterize the engineering properties of external-dump materials and representative foundation conditions; (ii) quantify the influence of dump height and pit-to-dump distance on FoS; (iii) investigate the effects of overall slope angle and weak geological horizons using 3DEC Numerical Modelling; and (iv) establish a site-specific Geotechnical framework for preliminary optimization of pit-to-dump distance for progressively deepening opencast coal mines.

The methodology extends conventional limit-equilibrium assessment through numerical sensitivity analysis. LEM provides an efficient representation of global slope stability and critical circular slip surfaces, whereas three-dimensional distinct-element modelling provides additional insight into stress redistribution, deformation localization and the influence of weak geological zones. The two approaches are therefore treated as complementary levels of geotechnical assessment rather than interchangeable computational methods. This integrated framework is consistent with established international geotechnical engineering practice in which material characterization, analytical stability assessment, Numerical Modelling and field verification are combined for complex slope systems. Previous numerical investigations of excavation-induced stress redistribution in underground coal mining have also shown that progressive excavation and goaf formation can increase stress transfer to adjacent support structures, with the location and magnitude of peak stress changing with the stage of extraction [15].



Figure 5.10. View of Mines A, B and C. Pictures showing collection of Overburden dump samples from Mines A, B and C

Figure 1. Field setting and collection of OB-dump samples from the selected case-study mines.

2 METHODOLOGY

2.1 Field investigation, geotechnical sampling and site characterization

Field investigations were undertaken at Mine A, Mine AI and Mine AII. A total of 27 representative OB samples were collected from different dump levels: nine from Mine A, eight from Mine AI and ten from Mine AII. The investigation programme considered the mine geometry, pit configuration, dump morphology, crest-to-dump relationship and foundation conditions relevant to dump placement. Particular attention was given to the changing spatial relationship between the advancing pit crest and external dumping areas, which becomes increasingly important as open-pit depth and dump elevation increase during mine development.

At Mine AII, Standard Penetration Tests (SPT) were undertaken near internal OB dumps to obtain an indication of near-surface foundation resistance and variability. Representative N-value ranges were 6–28 for Borehole 1, 4–17 for Borehole 2 and 6–75 for Borehole 3. The wide variation demonstrates that foundation density and resistance can change substantially over relatively short distances and depths. Such heterogeneity is an important geotechnical consideration when defining the critical load-transfer zone beneath an external dump and when selecting a representative foundation condition for stability modelling.

Borehole	Depth / material	N-value range
01	0.15–1.95 m; fine–medium sand, clayey zones	6–28
02	0.15–1.50 m; fine–medium grey sand	4–17
03	0.00–3.30 m; grey clayey/fine sand	6–75

Table 1. Representative SPT results used to describe foundation variability.

2.2 Laboratory geotechnical characterization and standardized testing

Laboratory characterization comprised particle-size distribution by sieve analysis in accordance with IS 2720

(Part 4), Standard Proctor compaction in accordance with IS 2720 (Part 7), specific gravity determination and direct shear testing in accordance with IS 2720 (Part 13). These standardized test procedures provide a traceable basis for deriving engineering parameters used in the stability assessment. The test programme follows established geotechnical characterization practice, with the measured properties subsequently incorporated into the analytical and numerical models rather than relying on generic or assumed dump-material parameters. The particle-size results indicated predominantly coarse material with limited fines. Maximum dry density was approximately 1.9–2.1 g/cc and optimum moisture content ranged from 0.8 to 9.3%. Specific gravity varied from 1.46 to 2.51.

Direct shear testing provided cohesion values of 3–13.5 kPa and friction angles of 26.9°–52°. Gravel-rich material generally exhibited greater frictional resistance, whereas fine-rich material produced comparatively lower shear-strength margins. The measured cohesion, friction angle and density parameters were used as model inputs, thereby maintaining a direct linkage between laboratory characterization and slope-stability assessment. In engineering terms, these parameters govern the available shear resistance along potential failure surfaces and the response of the dump–foundation system to surcharge loading.

Parameter	Investigated range
Number of OB samples	27
Cohesion, c	3–13.5 kPa
Friction angle, ϕ	26.9°–52°
Maximum dry density	1.9–2.1 g/cc
Optimum moisture content / specific gravity	0.8–9.3% / 1.46–2.51

Table 2. Summary of measured geotechnical properties of the OB material.

2.3 Empirical / limit-equilibrium stability analysis

Limit-equilibrium stability analyses were conducted using circular potential failure surfaces extending from the dump toe towards the adjacent pit-slope system. The Swedish slip-circle (Fellenius) and Bishop's Simplified approaches were considered. Dump heights of 30, 60, 90 and 120 m and pit-to-dump distances of 30, 60, 90 and 120 m were investigated, with dump slope angles within approximately 25°–37.5°. Dry-dump conditions were assumed and the surcharge effect of the external dump mass was incorporated into the stability assessment. The analyses were intended to represent the global stability response of the pit–dump system under the defined static loading configurations.

The Factor of Safety was treated as the ratio of available shear resistance to mobilized shear stress, and $FoS > 1.3$ was adopted as the static stability criterion for the investigated cases. Laboratory-derived unit weight, cohesion and friction angle were used as model inputs. Trial circular slip surfaces were evaluated by subdividing the potential sliding mass into slices and balancing driving and resisting forces. The parametric design isolates the principal influence of dump height and pit-to-dump distance while retaining the measured variability of the OB material. The approach provides an efficient screening-level framework before detailed numerical verification of critical geometries.

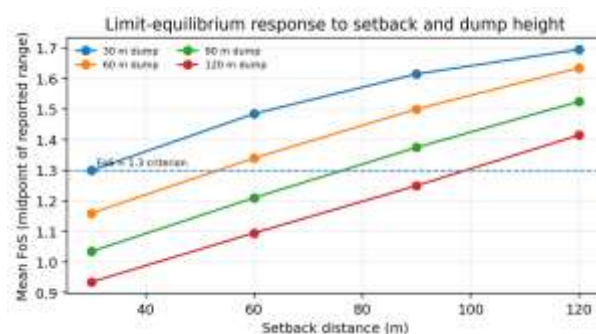


Figure 2. Derived mean FoS response for the LEM cases; values are midpoints of the reported FoS ranges in Table 3.

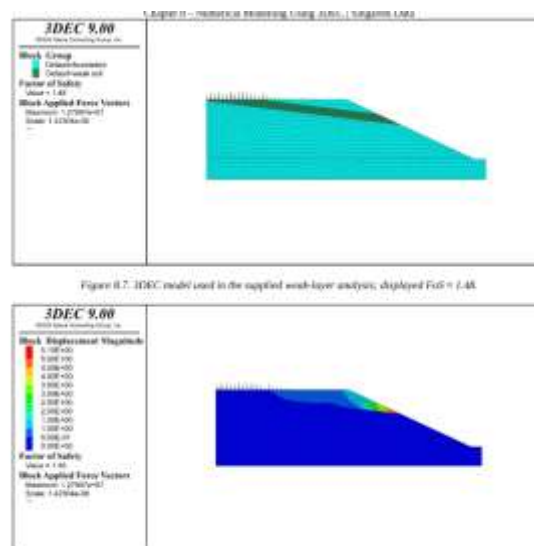
Dump height	30 m setback	60 m setback	90 m setback	120 m setback
30 m	1.28–1.32	1.46–1.51	1.59–1.64	1.68–1.71
60 m	1.14–1.18	1.31–1.37	1.47–1.53	1.61–1.66
90 m	1.02–1.05	1.19–1.23	1.35–1.40	1.50–1.55
120 m	0.92–0.95	1.08–1.11	1.23–1.27	1.39–1.44

Table 3. FoS ranges across Mine A, II and III for each dump-height and setback combination.**2.4 Three-dimensional numerical modelling investigation using 3DEC**

A supplementary three-dimensional distinct-element sensitivity analysis was carried out using 3DEC to examine the coupled influence of overall slope angle, pit-to-dump distance, geological condition and external-dump surcharge. The supplied numerical framework considered overall slope angles of 25°, 30°, 35°, 40° and 45°; pit-to-dump distances of 25, 50, 75 and 100 m; a critical dump height of 120 m; and homogeneous, sandstone-dominated and weak-layer foundation conditions. The critical numerical geometry also represented a deep-pit condition with a pit depth of approximately 150 m, reflecting the progressive deepening context addressed by the research.

Under the homogeneous 25 m setback sequence, the supplied 3DEC results show FoS decreasing from 2.390 at 25° to 2.008 at 30°, 1.789 at 35°, 1.621 at 40° and 1.477 at 45°. For the weak-layer cases, the mean FoS increased from 1.242 at 25 m setback to 1.305, 1.355 and 1.382 at 50, 75 and 100 m, respectively. These results are interpreted as a numerical sensitivity assessment of the principal LEM trend, with emphasis on the interaction between pit-slope geometry, surcharge position and foundation condition.

The weak-layer model explicitly represents a relatively incompetent geological interlayer between stronger foundation materials. The numerical outputs show localized deformation towards the slope face and within the region influenced by the weak layer. Thus, the 3DEC analysis provides qualitative information on deformation localization and potential load-transfer mechanisms in addition to the reported global FoS. In a detailed mine-design application, analogous modelling can be extended to explicitly mapped geological discontinuities or fault-controlled zones where field investigations identify such structures.

**Figure 3. Supplied 3DEC weak-layer model and deformation/output profile; displayed FoS $\approx$ 1.48 for the illustrated configuration.**

3DEC case	Key condition	FoS
Homogeneous	25° slope, 25 m setback	2.390
Homogeneous	30° slope, 25 m setback	2.008
Homogeneous	35° slope, 25 m setback	1.789
Homogeneous	40° slope, 25 m setback	1.621
Homogeneous	45° slope, 25 m setback	1.477

Table 4. Selected homogeneous-foundation 3DEC results at 25 m setback.**3 RESULTS AND DISCUSSION****3.1 Geotechnical characterization, foundation competence and stability implications**

The measured engineering properties demonstrate that the external-dump material is markedly heterogeneous. Cohesion varies from 3 to 13.5 kPa and friction angle from 26.9° to 52°, while specific gravity varies from 1.46 to 2.51. These ranges are sufficiently large to influence the available shear resistance of the potential sliding mass and, consequently, the calculated stability margin. The SPT results likewise indicate substantial variability in near-surface foundation resistance. Therefore, defining pit-to-dump distance from a single representative material value may mask localized weak zones and may not adequately represent the

governing geotechnical condition.

The laboratory programme is particularly significant because the direct-shear parameters are used directly in the LEM calculations, while density, gradation and compaction characteristics support interpretation of dump behaviour and stress transfer. The predominantly coarse gradation and low OMC values are consistent with largely granular dump material; however, fine-rich zones require additional caution because lower shear resistance and moisture-induced changes in effective stress can reduce the stability margin. This reinforces the need for standardized material characterization and representative parameter selection when assessing external dumps adjacent to deepening pits.

3.2 Limit-equilibrium response to dump surcharge, dump height and pit-to-dump distance

The LEM results demonstrate a consistent geometric and loading response. Increasing pit-to-dump distance reduces the surcharge influence on the adjacent pit slope and consequently increases FoS. Conversely, increasing dump height increases the magnitude and spatial extent of loading transmitted through the dump and foundation, resulting in a lower FoS at the same setback. For a 30 m dump, the reported FoS range rises from 1.28–1.32 at 30 m setback to 1.68–1.71 at 120 m setback. For a 60 m dump, the corresponding range increases from 1.14–1.18 to 1.61–1.66.

The destabilizing effect becomes more pronounced at higher dump elevations and shorter setbacks. For the 90 m dump, the reported FoS range is 1.02–1.05 at 30 m setback and 1.35–1.40 at 90 m setback. For the 120 m dump, the FoS range remains below 1.3 at 30, 60 and 90 m setbacks and reaches 1.39–1.44 at 120 m. The high-dump/short-setback configuration therefore represents the most demanding condition in the investigated LEM matrix. From a geotechnical design perspective, the results demonstrate that dump elevation cannot be considered independently of pit-to-dump distance, particularly as open-pit deepening increases the height and potential consequence of the adjacent slope system.

The regression relationship developed from the study is:

$$\text{FoS} = 2.95 + 0.064\phi + 0.112c - 0.089Uw - 0.003H + 0.007Sd$$

where ϕ is friction angle ($^{\circ}$), c is cohesion (kPa), Uw is unit weight, H is dump height (m) and Sd is pit-to-dump setback distance (m). The model achieved $R^2 = 0.742$ and was reported to predict FoS within approximately $\pm 10\%$ of the numerical results. It should therefore be treated as a preliminary screening relationship for mine planning and sensitivity assessment, and not as a substitute for site-specific geotechnical investigation, detailed stability analysis or numerical verification of critical configurations.

3.3 3DEC numerical modelling: slope geometry and pit-to-dump distance

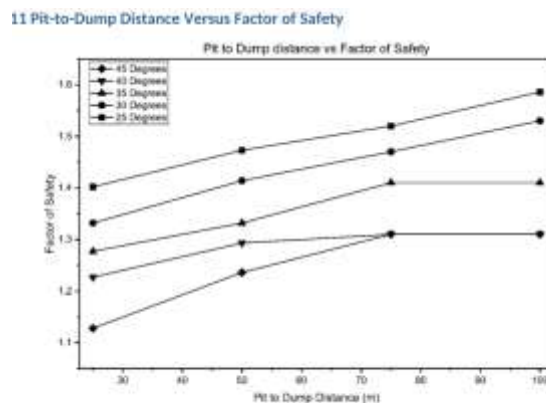


Figure 4.4: Supplied plot of pit-to-dump distance versus Factor of Safety for different overall slope angles.

The supplied plot provides the graphical representation of the sensitivity analysis. In general, the curves show that

Figure 4. Supplied 3DEC sensitivity plot showing FoS as a function of pit-to-dump distance for different overall slope angles.

The 3DEC sensitivity plot independently supports the observed pit-to-dump distance trend. At each investigated overall slope angle, increasing the distance from the pit crest generally increases FoS. The magnitude of the improvement is more pronounced for the steeper slope configurations, indicating that the geotechnical significance of setback increases as the slope geometry becomes less favourable. This behaviour is particularly relevant to progressively deepening open pits, where changes in overall slope height and geometry may increase the demand on the slope system while external dumping areas become spatially constrained.

The homogeneous numerical sequence provides a useful baseline for evaluating the effect of slope geometry. At a fixed 25 m setback, increasing the overall slope angle from 25° to 45° reduces FoS from 2.390 to 1.477. This progressive reduction demonstrates that horizontal separation between the dump and pit crest cannot be interpreted independently of the overall slope configuration. A setback that provides an adequate stability margin for a relatively flatter geometry may be insufficient when the pit slope becomes steeper or deeper. The numerical sensitivity therefore supports the use of a coupled pit-geometry and pit-to-dump-distance design

approach.

3.4 Weak-layer, geological-discontinuity and deformation response

The weak-layer simulations introduce a geological mechanism that is not represented explicitly by a homogeneous LEM material. The mean FoS increases from 1.242 at 25 m setback to 1.382 at 100 m setback. The increase confirms that increasing pit-to-dump distance reduces the destabilizing influence of surcharge under weak-layer conditions. The response also demonstrates that the same geometric setback may produce different stability margins depending on the competence, orientation and location of the underlying geological horizon.

The deformation output in Figure 3 shows concentration of higher displacement towards the slope face and near the weak-layer-influenced region. This is important for geotechnical management because global FoS alone does not identify the spatial distribution of deformation. Numerical deformation contours can therefore be used to identify critical monitoring zones near the crest, upper slope and locations where geological discontinuities intersect the pit wall or foundation. Such information is particularly relevant during progressive dump construction and pit deepening, when the load-transfer environment changes continuously.

The supplied numerical framework also indicates that weak-layer orientation affects the calculated FoS. The orientation cases were modelled at 5°, 6°, 7° and 8°, with corresponding changes in depth and geometry. Because orientation and depth vary together in the supplied matrix, the effect should be interpreted as a combined sensitivity rather than as a fully isolated orientation effect.

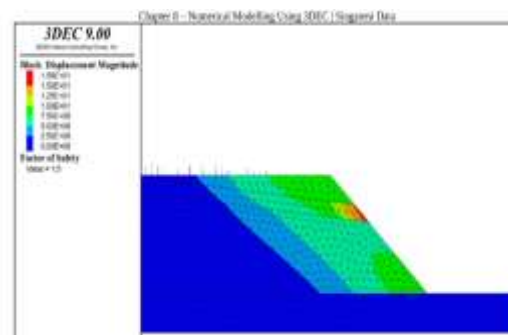


Figure 5. Representative supplied 3DEC output contour, showing the deformation field and displayed FoS $\approx$ 1.50.

3.5 Integrated geotechnical interpretation and design implications

The LEM and 3DEC results consistently identify pit-to-dump distance and dump height as important controls on the stability of the pit-dump system. LEM provides an efficient two-dimensional screening framework for multiple dump heights and measured material conditions, while 3DEC provides three-dimensional insight into deformation localization and the influence of weak geological conditions. The results should not be interpreted as numerically identical cases because the geometries, idealizations and solution procedures differ; rather, the numerical analysis provides an independent assessment of the governing geotechnical sensitivities.

For the case-study conditions investigated in the LEM study, 60 m is associated with FoS above 1.3 for dumps up to 60 m high, 90 m for 90 m high dumps and 120 m for 120 m high dumps across the three case mines. These values describe the tested dry-condition configurations and should not be treated as universal regulatory setbacks.

A practical geotechnical design sequence is therefore recommended: first establish the proposed dump height, bench configuration and final pit geometry; second characterize the dump and foundation materials using representative field and laboratory investigations; third undertake LEM screening over the relevant range of dump heights and pit-to-dump distances; fourth subject critical configurations involving steep slopes, high dumps, weak layers or structural discontinuities to three-dimensional numerical modelling; and finally verify the selected design through field monitoring during progressive dump development. Where the required FoS is not achieved, possible design responses include increasing setback, reducing dump height, modifying bench geometry, improving drainage, controlling dumping sequence or applying suitable stabilization measures.

Groundwater, rainfall, blasting, dump sequencing and progressive loading were not fully represented in the principal dry-condition LEM matrix. These factors can modify pore-water pressure, effective stress, material strength and deformation response and should therefore be incorporated in detailed design where relevant. The reported distances should consequently be treated as site-specific preliminary design envelopes for the investigated conditions and verified against actual mine geometry, foundation response and prevailing hydrogeological conditions before implementation. [16, 17]

For a progressively deepening opencast mine, the selected pit-to-dump distance should be treated as a dynamic geotechnical design parameter rather than a one-time geometric constraint. As the pit advances, the highwall/overall slope geometry changes, dump elevation increases and the load-transfer path evolves. The governing design case should therefore be re-analysed at critical intermediate and final dump elevations.

Continuous geotechnical monitoring is important because stability conditions can change as dumping progresses, the pit deepens, drainage conditions evolve or previously unrecognized weak zones are exposed. The present LEM study assumes dry dump conditions and uses a two-dimensional idealization. Consequently, the reported setback values should not be interpreted as universal distances for all seasons, geological conditions or mine geometries. Rainfall infiltration, groundwater pressure, blasting vibration, progressive construction, changes in dump density and local foundation weakness can alter the stability response. The 3DEC sensitivity results provide additional insight into slope angle, pit-to-dump distance and weak-layer effects, but they also represent defined numerical configurations rather than every possible field condition. These limitations should be explicitly considered when transferring the methodology to other mining areas.

3.6 Proposed geotechnical design workflow and applicability

The study avoids treating pit-to-dump distance as a fixed geometric number. Instead, the selected distance is considered the output of an iterative geotechnical design process in which dump height, material strength, foundation competence, pit-slope geometry, geological structure and loading conditions are evaluated together. If the calculated FoS is inadequate, the design response may include increasing pit-to-dump distance, reducing dump height, modifying the slope profile, improving drainage or applying appropriate stabilization measures. This framework is particularly relevant where mine planning requires progressive dumping close to an advancing and deepening pit and where the final dump geometry changes with time.

For practical mine planning, the following workflow can be adopted for external-dump setback assessment. First, establish the proposed dump height, bench geometry and final crest-to-crest/pit-to-dump configuration from the mine plan. Second, characterize representative dump and foundation materials for gradation, density, compaction and shear strength using standardized laboratory procedures. Third, establish groundwater and drainage conditions because effective stress controls the available shear resistance. Fourth, use LEM to screen a matrix of dump heights and pit-to-dump distances and identify configurations approaching the required FoS. Fifth, examine critical configurations involving steep overall slopes, high dumps, weak layers, faults or strong material variability using three-dimensional numerical modelling. Finally, verify the selected configuration through field monitoring of crest movement, surface displacement and other relevant geotechnical indicators during progressive dump construction and pit deepening.

3.7 Integrated numerical interpretation and engineering design framework

The third important observation is the role of geological variability. The laboratory programme produced a broad range of strength parameters, while the field SPT results showed variation in near-surface resistance. The 3DEC weak-layer model further demonstrates that a discrete or distributed low-strength geological horizon can modify deformation patterns and the stability response. These observations support a staged assessment in which preliminary pit-to-dump distance is screened using LEM and critical geological configurations are subsequently examined through three-dimensional numerical modelling.

A second common trend is the influence of slope geometry. The homogeneous 3DEC sequence shows a reduction in FoS from 2.390 to 1.477 as the overall slope angle increases from 25° to 45° at the same 25 m setback. The LEM analysis similarly identifies lower stability margins for configurations in which dump loading and slope geometry are less favourable. Thus, pit-to-dump distance should be established together with the final pit geometry, particularly where progressive deepening increases overall slope height and changes the stress regime within the slope mass.

The analytical and numerical results show a common physical trend: increasing the distance between the external dump and pit crest reduces the destabilizing influence of dump surcharge. In the LEM matrix, the improvement is observed across the investigated dump heights. In the 3DEC weak-layer sensitivity, mean FoS rises from 1.242 at 25 m setback to 1.382 at 100 m. The agreement in trend strengthens the interpretation that pit-to-dump distance is an important geometric control on the stability response, although the appropriate value remains dependent on site-specific geotechnical and geological conditions.

The combined evidence also supports a clear distinction between preliminary planning and final geotechnical design. LEM is efficient for screening multiple dump-height and setback combinations and for comparing the three case-study mine material conditions. 3DEC is more useful for selected critical configurations where geological structure, three-dimensional deformation or weak-layer behaviour requires closer examination. The final design process can therefore use LEM to establish a preliminary stability envelope and numerical modelling to interrogate critical configurations before field implementation.

For the integrated assessment, the numerical results can be considered at three levels. The first is global FoS, which indicates the overall stability margin. The second is the sensitivity of FoS to pit-to-dump distance, dump height and slope angle, which identifies the governing geometric variables. The third is the deformation pattern, which indicates where the numerical model predicts greater movement or strain concentration. Considering all three levels provides a more comprehensive engineering interpretation than relying on a single global FoS value.

The deformation contours provide an additional interpretation of the numerical results. The displacement field is concentrated toward the upper and face regions of the slope, with higher displacement represented by the warmer portions of the supplied contour. The weak-layer model also displays a distinct change in response

around the low-strength zone. Such patterns can be used to identify where field monitoring should be concentrated, particularly near the crest, upper slope and locations where geological discontinuities intersect the pit wall or foundation.

The matrix also illustrates why the influence of pit-to-dump distance is not necessarily linear across all configurations. At low setbacks, moving the dump farther from the crest removes a greater portion of the surcharge influence from the critical slope region. At larger setbacks, the incremental increase in FoS becomes smaller in several cases, indicating diminishing sensitivity once the dump load is sufficiently separated from the crest. This behaviour is useful for mine planning because it supports selection of a distance at which the required stability margin is achieved rather than simply maximizing separation.

At 40° slope angle, the 5° weak-layer case increases from 1.227 at 25 m to approximately 1.31 at 75–100 m. At 35°, the same orientation increases from 1.277 to 1.40, while at 30° it increases from 1.332 to 1.53. The sequence demonstrates that flatter overall slope geometries retain a larger stability margin for the same weak-layer orientation and setback. This is consistent with the homogeneous sequence, where FoS also decreases as slope angle increases.

The weak-layer matrix provides a more detailed view of how slope angle and setback interact when a lower-strength geological zone is present. At the 45° overall slope, the reported FoS values remain relatively low over the tested setbacks, with the 5° orientation increasing from 1.128 at 25 m to 1.31 at 75–100 m. The corresponding 6° case rises from 1.164 at 25 m to 1.184 at 100 m, while the 7° and 8° cases show similarly constrained stability margins. These results indicate that increasing setback can improve the response, but the benefit is moderated when the overall slope is steep and the weak layer is unfavourably positioned.

3.8 Detailed interpretation of the weak-layer matrix

A monitoring-based geotechnical management approach is particularly important because the stability calculation represents a defined loading and geological condition. Actual mine conditions evolve continuously as dumping progresses, rainfall changes the moisture regime, drainage paths develop and the pit advances and deepens. The selected pit-to-dump distance should therefore form part of an ongoing geotechnical management process rather than being treated as a one-time geometric decision.

The numerical deformation patterns provide a useful basis for planning field monitoring. The supplied 3DEC contours indicate greater deformation towards the slope face and near the region affected by the weak layer. During actual dump construction, monitoring can therefore be concentrated at the crest, upper slope and locations where geological discontinuities intersect the slope. Measurements of crest movement, displacement trends and changes in surface condition can be used to identify whether the field response remains consistent with the design assumptions.

3.8.1 Implications for geotechnical monitoring

The LEM matrix provides a practical example of the balance between stability margin and operational separation. For 60 m high dumps, the FoS range rises from 1.14–1.18 at 30 m setback to 1.61–1.66 at 120 m setback. For 90 m high dumps, the corresponding increase is from 1.02–1.05 to 1.50–1.55. These results demonstrate that increasing separation can substantially increase the stability margin, but the required pit-to-dump distance remains dependent on dump height and the governing geotechnical condition. The same principle is visible in the 3DEC weak-layer analysis, where mean FoS increases as setback is increased from 25 to 100 m.

From an operational perspective, increasing pit-to-dump distance has both geotechnical and mine-planning consequences. Greater separation reduces surcharge influence and generally increases the stability margin, but it also increases the dumping footprint and may increase haulage distance, cycle time and energy demand. The purpose of the present study is therefore not to maximize setback irrespective of operational requirements, but to establish a stability-based design envelope from which an appropriate distance can be selected for a particular dump height, pit geometry and material condition.

3.8.2 Operational significance of pit-to-dump distance

The numerical output should therefore be interpreted in conjunction with the field investigation. A high FoS obtained from a homogeneous model does not demonstrate that every geological section is equally stable. Where field mapping, borehole information or SPT results indicate weak zones, those conditions should be represented explicitly in the detailed geotechnical model. This is particularly important for external dumps located close to pit crests, where a relatively small change in foundation competence can modify the load-transfer mechanism and deformation response.

Foundation condition is another major source of uncertainty. The SPT data show N-values ranging from 4 to 75 across representative boreholes, indicating changes in density and resistance with depth and location. A strong foundation can distribute dump loading more effectively, whereas a weaker foundation may permit greater deformation or reduce the available resistance along a potential sliding zone. The 3DEC weak-layer simulations provide a numerical representation of this effect by placing a low-strength layer between stronger materials.

3.8.3 Influence of foundation competence

The implication for mine planning is that pit-to-dump distance should be considered together with the final

dump elevation and the progressive deepening of the pit. A moderate setback may be adequate during early dumping stages but become inadequate as the dump is progressively raised or the pit geometry evolves. Therefore, a staged dump-development plan should be accompanied by repeated stability checks at intermediate and final elevations. Numerical modelling is particularly useful for examining the critical final geometry where dump height, slope angle and foundation condition combine to produce the greatest loading demand.

Dump surcharge is transmitted through the dump mass to the underlying foundation and adjacent pit-slope system. As the dump is raised, both the magnitude and the spatial distribution of the imposed load change. The LEM results show that this effect is captured by the progressive reduction in FoS as dump height increases from 30 to 120 m. At the same setback, the 120 m dump consistently gives the lowest stability margin. This is particularly evident at 30 m setback, where the reported FoS range falls to 0.92–0.95 for the 120 m dump compared with 1.28–1.32 for the 30 m dump.

3.8.4 Influence of dump surcharge and progressive loading

Dump surcharge is a major factor controlling the stability of the pit-dump system, particularly where the external overburden dump is located close to the pit crest. As the dump height increases, the magnitude and spatial distribution of the surcharge transmitted through the dump and foundation also increase. The limit-equilibrium results demonstrate a consistent reduction in Factor of Safety (FoS) with increasing dump height at a given pit-to-dump distance. For example, at a 30 m setback, the FoS range decreases from 1.28–1.32 for a 30 m high dump to 0.92–0.95 for a 120 m high dump. Similarly, at a 120 m setback, the FoS ranges from 1.68–1.71 for a 30 m high dump to 1.39–1.44 for a 120 m high dump, indicating that the influence of dump height remains significant even at larger setbacks.

The results further indicate that the effect of surcharge is strongly dependent on pit-to-dump distance. Increasing the setback reduces the proportion of dump loading influencing the critical slope region and consequently improves the stability margin. This trend is also supported by the 3DEC sensitivity analysis, in which the mean FoS under weak-layer conditions increased from 1.242 at 25 m setback to 1.382 at 100 m setback. Thus, the numerical results independently support the LEM observation that greater separation between the dump and pit crest reduces the destabilizing influence of external dumping.

Progressive loading is particularly important in a deepening opencast mine because dump construction generally occurs in stages. As the dump is progressively raised, the loading condition beneath the dump and adjacent pit slope changes continuously. Therefore, a setback that provides an acceptable stability margin during the initial stages of dumping may become less favourable at higher dump elevations. The study results show that the 120 m dump represents the most critical dump-height condition among the investigated LEM cases, with FoS remaining below 1.3 at 30, 60 and 90 m setbacks and exceeding 1.3 only at the 120 m setback under the specified dry-condition assumptions.

The 3DEC results additionally demonstrate that surcharge response is coupled with overall slope geometry and foundation condition. At a constant 25 m setback, the homogeneous-model FoS decreased from 2.390 at 25° slope angle to 1.477 at 45°, demonstrating that the same surcharge condition can produce different stability responses as the slope geometry changes. Under weak-layer conditions, the deformation contours also show greater deformation towards the slope face and near the weak geological zone, indicating that surcharge loading may influence not only the global FoS but also the spatial distribution of deformation.

Accordingly, progressive dump loading should be incorporated into mine-specific geotechnical design through stability checks at intermediate and final dump elevations. Dump height, pit-to-dump distance, slope geometry, foundation competence and geological conditions should be considered together rather than independently. Where stability margins become inadequate during progressive loading, appropriate design responses may include increasing the setback distance, reducing dump height, modifying the dump or pit-slope geometry, improving drainage, controlling the dumping sequence, or adopting suitable stabilization measures.

3.9 Comparison of analytical and numerical trends

The numerical results also demonstrate why a single pit-to-dump distance should not be transferred directly from one geological condition to another. For example, a 100 m setback in a weak-layer model may provide a higher FoS than a shorter setback, but the resulting value still depends on slope angle, weak-layer geometry and dump loading. Similarly, the LEM result for a 120 m dump at 120 m setback is not numerically equivalent to a 3DEC 120 m dump model because the two analyses use different geometrical idealizations and solution procedures. The appropriate engineering use of the numerical results is therefore to identify governing sensitivities and critical configurations requiring detailed site-specific assessment.

The weak-layer simulations add a second geotechnical mechanism. The interlayer provides a lower-strength zone between stronger foundation materials and can influence both the location and magnitude of deformation. The supplied weak-layer matrix considers orientations of 5°, 6°, 7° and 8°, with corresponding changes in depth from the crest. Because orientation and depth change together, the results are interpreted as a combined structural sensitivity rather than as a fully isolated orientation effect. The mean FoS increases from 1.242 at 25 m setback to 1.305 at 50 m, 1.355 at 75 m and 1.382 at 100 m.

The homogeneous cases provide a baseline for understanding the effect of slope geometry. At a 25 m setback,

the calculated FoS decreased progressively from 2.390 at 25° to 2.008 at 30°, 1.789 at 35°, 1.621 at 40° and 1.477 at 45°. The numerical sequence therefore demonstrates that increasing overall slope angle reduces the stability margin even when pit-to-dump distance is kept constant. This behaviour is consistent with the mechanics of a steeper slope, for which the driving component of the weight of the potentially unstable mass becomes more significant.

The 3DEC analysis was used as a sensitivity framework rather than as a direct replacement for the limit-equilibrium calculations. The principal variables were overall slope angle, pit-to-dump distance, foundation condition and the presence of a weak layer. The critical numerical geometry included a 150 m pit depth and a 120 m dump height, while overall slope angles of 25°, 30°, 35°, 40° and 45° and setbacks of 25, 50, 75 and 100 m were investigated. Homogeneous, sandstone-dominated and weak-layer conditions were considered to examine how the response changes when the foundation is idealized differently. Where mapped faults or other structural discontinuities are present in an actual mine, the same framework can be extended through explicit discontinuity modelling during detailed design.

4 CONCLUSIONS

This study integrates standardized geotechnical characterization, limit-equilibrium stability analysis and three-dimensional distinct-element numerical sensitivity modelling to investigate the safe and operationally efficient placement of external OB dumps adjacent to progressively deepening selected opencast coal mines in the Godavari Valley Coalfields. The principal conclusions are:

- (1) The OB material is heterogeneous, with measured cohesion of 3–13.5 kPa, friction angle of 26.9°–52°, maximum dry density of approximately 1.9–2.1 g/cc, OMC of 0.8–9.3% and specific gravity of 1.46–2.51. Foundation investigations also showed substantial spatial variability in SPT N-values, demonstrating the importance of representative foundation characterization.
- (2) FoS increases systematically with pit-to-dump distance and decreases with dump height. Under the investigated dry-condition LEM assumptions, setbacks of 60, 90 and 120 m correspond to FoS above 1.3 for dump heights up to 60, 90 and 120 m, respectively, across the three case mines. These values constitute site-specific analytical results for the investigated configurations and are not universal regulatory setbacks.
- (3) The regression relationship $FoS = 2.95 + 0.064\phi + 0.112c - 0.089Uw - 0.003H + 0.007Sd$ achieved $R^2 = 0.742$ and can be used as a preliminary screening relationship for mine-planning sensitivity assessment.
- (4) The 3DEC sensitivity analysis confirms the influence of slope geometry and pit-to-dump distance. For the homogeneous 25 m setback sequence, FoS decreased from 2.390 at 25° to 1.477 at 45°. Under weak-layer conditions, mean FoS increased from 1.242 at 25 m setback to 1.382 at 100 m.
- (5) Numerical deformation outputs indicate that weak geological layers can influence the location and concentration of deformation near the slope face. Consequently, geological structure, foundation competence and potential discontinuities should be incorporated explicitly in detailed stability assessment where field investigations identify such conditions.
- (6) Optimum pit-to-dump distance should be established as a function of dump height, slope geometry, measured material properties, foundation competence, geological structure and the progressive geometry of the deepening pit. The distances derived in this study are site-specific design envelopes and require verification through detailed numerical modelling, hydrogeotechnical assessment and field monitoring before implementation.

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