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Study on the impact of surface waste dumps operations on the behavior of roadway structures in mine

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ABSTRACT

The rapid development of mining activities has led to the formation of numerous massive surface waste dumps. The presence of these dumps creates an extremely large source of artificial loads, negatively impacting the stability of the mine roadway system. However, there are many current methods for calculating and designing support structures that often ignore the influence of surface waste dump loads, leading to many deformation and structural failure incidents in practice. This study focuses on systematically evaluating the influence of surface waste dump loads on the behaviour of the roadway support structure. A numerical model was developed using the Phase 2 software with overall dimensions of 500 × 250 m (width × height). The roadway was designed with a straight-wall semicircular arch cross-section, having a width of 5 m and a height of 5 m. The investigated roadway was located at a depth of 50 m below the ground surface within a homogeneous rock mass. In this study, the waste dump is simulated using a trapezoidal load with a small base width of 100 m, a large base width of 300 m, and a load pressure of 5 MN/m (equipvalent to dump height at 250 m, unit weight 20 kN/m^3 thereof) applied to the top surface of the model. The Hoek-Brown failure criterion is assigned to a homogeneous and isotropic rock mass located beneath the waste dump. The study investigated the effects of varying the unit weight of the waste dump material and the waste dump height on the internal forces developed in the roadway support system. The simulation results demonstrate that increasing both the unit weight and height of the waste dump significantly intensifies the loading on the roadway support structure, resulting in greater axial forces, bending moments. These findings provide a scientific basis for accurately assessing the influence of surface waste dumps, optimizing roadway support design, improving long-term stability, and enhancing the safety and economic efficiency of underground mining operations beneath waste dump areas.

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1. Introduction

Quang Ninh is the largest coal mining centre in Vietnam, playing a key role in national energy security. Open-pit and underground mining processes in Cam Pha, Hon Gai, and Uong Bi areas have generated huge amounts of waste rock, creating large-scale surface waste dumps such as Cao Son, Bang Nau, Chinh Bac,… with waste dumping heights that can reach 120 ÷ 540 m. Notably, many of these waste dumps are located directly on areas with coal seams and roadway systems being mined below.

The existence of surface waste dumps changes the initial stress state in the rock mass, creating additional artificial loads acting on underground structures (McLemore et al., 2009; Robertson, 1982; Wickland and Wilson, 2005; Anterrieu et al., 2010). Production practices at the Mong Duong, Khe Cham, and Nui Beo mines show that roadways located beneath the waste dump frequently experience severe deformation, subsidence, and compression of the supporting structures, more so than areas unaffected by the waste dump. At the Mong Duong mine, many tunnels were compressed, reducing the usable area from 5÷11 m^2, requiring multiple expansions and support work, resulting in increased costs and safety risks (Figure 1).

Figure 1. Deformation and subsidence in transport tunnel at the Mong Duong mine.

Although mine waste dumps can be classified in various ways according to location (inside/outside), terrain (valley/slope) or dump creation technology (Tachie-Menson, 2006; Wilson, 2000; Yang et al., 2006; Zhang et al., 2011; Fredlund, 1984), the assessment of their impact on underground structures is still limited:

- Theoretical methods: The pressure hypotheses of Protodiakonov and Tsimbarevich (Hoek & Brown, 1980) only consider the weight of rock on the mine roof and do not take into account the depth of the tunnel and additional loads from the surface. The theories of Bierbaumer (Bickel et al., 1996) and Terzaghi (Terzaghi, 1946), although they take into account depth, only apply to shallow tunnels or roadway entrance areas. Therefore, there are no specific quantitative guidelines for roadways located deep under waste dumps hundreds of meters high.
- Numerical methods: A 2D simulation using software such as FLAC, UDEC, Plaxis, and Phase^2 has been applied to simulate the stress-strain state of the rock mass (Itasca Consulting Group. (2019); Itasca Consulting Group. (2021); Bentley Systems. (2024); Rocscience Inc. (2021)). However, domestic (Vietnam) studies have only approached this at a preliminary level. Some initial results mainly stop at surveying the influence of the waste dump on the displacement of vertical shafts or a few specific roadways; finding the detailed law of internal force distribution in the structure to optimise the structural parameters of steel support structures has not yet been systematically studied.
- Gap in international research: In the world, research works related to surface waste dumps mostly focus on the problem of slope stability under the influence of surface water and groundwater (Zhan et al., 2006; Zhou et al., 2009), risk assessment, ecological restoration, or temperature field variation due to the self-ignition of waste rock and interbedded rock (Bao et al., 2019; Zhao et al., 2021; Lin et al., 2021; Li et al., 2023; Du et al., 2022; Bai et al., 2025). At the same time, the approaches to waste dump planning mainly prioritize minimizing mine acid emissions (Wickland and Wilson, 2005). Due to the unique geological characteristics of large countries (such as China or European and American countries), coal seams are often located at very great depths or in waste disposal areas that do not overlap with underground mining systems. Therefore, quantitative studies on the complex interplay of "waste dump - rock mass - mine tunnel - support structure" have hardly been published.

In the context of expanding waste dumps and increasingly deeper underground mining, quantitatively assessing the impact of artificial pressure from waste dumps on the behaviour of the roadway structures is a pressing requirement. This study focuses on building and verifying a 2D numerical model to analyze the impact of a typical trapezoidal positive waste dump on the roadway below. The model surveyed for a roadway is U-shaped with a straight wall and semicircular arch (5 × 5 m) represents an open support structure, under the assumption of a homogeneous rock mass. The weight of the waste dump is assigned by the distributed load acting directly on the model in numerical simulation. The research results provide an important scientific basis for optimizing the selection of cross-sectional shape and parameters of steel support structures, ensuring safety and economic efficiency for coal mines in Quang Ninh.

2. Numerical model

2.1. Numerical model for the U-shaped roadway

This study implemented a 2D plane strain model based on the finite element method using Phase^2 software. The numerical model allows simultaneous simulation of geological conditions, surface waste dump loads, roadway structures, and construction phases under real-world conditions. The results can provide data on internal forces, stress distribution, and strain in the roadway structure.

A 6-node triangular element is used to describe the rock mass. The number of elements and nodes on whole model are 41274 and 83356 respectively. All elements are meshed well in quality. The model has dimensions of 500 m wide and 250 m high. The model surface is freely assigned, while horizontal displacement is restricted to the two edges of the model, vertical displacement is assigned to the bottom of the model, and all directions are fixed at the two bottom corners (Figure 2).

In this study, the waste dump is simulated using a trapezoidal load with a small base width of 100 m, a large base width of 300 m, and a load pressure of 5 MN/m (equipvalent to dump height at 250m, unit weight 20 kN/m^3 thereof) applied to the top surface of the model. The Hoek-Brown failure criterion (Hoek et al., 2002) is assigned to a homogeneous and isotropic rock mass located beneath the waste dump (Table 1). The steps for constructing the numerical model and verifying the model include:

Table 1. Properties of rock mass.

Parameter	Unit	Value
Weight	MN/m^3	0.0262
Young's Modulus	MPa	4611
Poisson's ratio	-	0.3
Intact uniaxial compressive strength	MPa	37.8
GSI	-	50
Intact rock material constant, mi	-	7
Disturbance factor, D	-	0.5
m_b		0.6472
s		0.0013
a		0.5057
Lateral earth pressure coefficient (K_0)	-	0.5
Failure criterion	-	Hoek-Brown

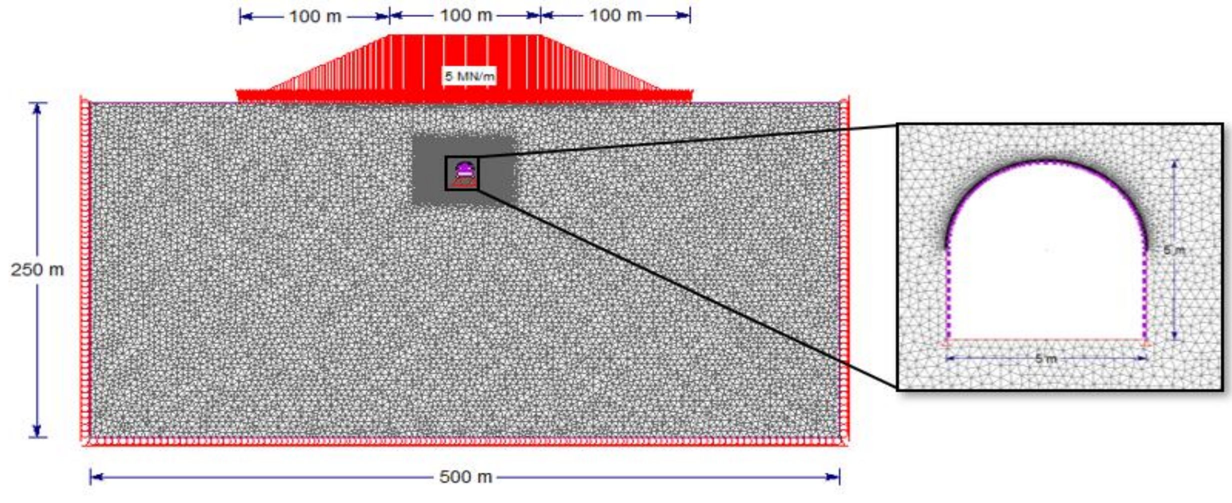

Figure 2. Geometric dimensions of the model.

- Step 1: Constructing the numerical model with a homogeneous rock mass;

- Step 2: Assigning the trapezoidal load to the surface model; This step will verify the reliability of the numerical model with Hamilton Gray's solution for linearly distributed loads, including trapezoidal loads - suitable for the surface waste dump model in this study under the same boundary conditions.

- Step 3: Excavate and apply the roadway support structure.

2.2. Comparison of numerical and analytical models for the problem of a semi-infinite space subjected to surface loading

The problem considers the rock environment as a two-dimensional semispace Oxz with the Ox axis as the horizontal direction and the Oz axis representing depth. This space has no dimension limitations along the Ox and Oz axes and is assumed to be elastic and isotropic in all directions. According to classical mechanics, when an external force is applied to a semi-infinite space, the rock elements in the environment will be affected by the external force and form internal forces (stresses) that tend to resist the deformation of the rock elements caused by the external force. The intensity of the distribution of internal forces per unit area is called the additional stress caused by the external force and is analysed into stress components along the directions of the soil and rock elements under study. The solution to the problem of distributing additional stress in an elastic semi-infinite space subjected to surface loading has been published by many authors. For example, Boussinesq in 1885 provided a solution to the problem of concentrated loads and uniformly distributed loads on an infinitely elastic half-space surface. Regarding the problem of additional stress distribution due to trapezoidal loads, Hamilton Gray (Gray, 1936) published results as shown in Figure 3 and formulas 1÷4.

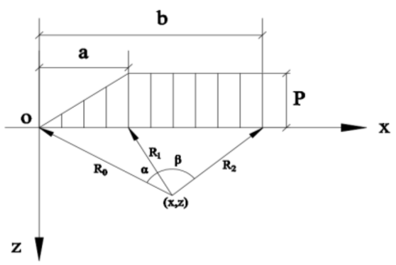

Figure 3. Scheme for calculating the semi-infinite space.

The x- and z-axis stress results of any stress element in an elastic infinite half-space are calculated using the formula:

- Normal stress, σ_x , σ_z *and* σ_y

$$\sigma_x = \frac{p}{\pi a}\left[\alpha\beta + x\alpha + \frac{az}{R_2^2}(x-b) + 2zlog_e\left(\frac{R_1}{R_0}\right)\right] \quad (1)$$

$$\sigma_z = \frac{p}{\pi a}\left[\alpha\beta + x\alpha - \frac{az}{R_2^2}(x-b)\right] \quad (2)$$

$$\sigma_z = \frac{p}{\pi a}\left[\alpha\beta + x\alpha - \frac{az}{R_2^2}(x-b)\right] \quad (3)$$

- Shear stress:

$$\tau_{xz} = -\frac{p}{\pi a}\left[z\alpha - \frac{az^2}{R_0^2}\right] \quad (4)$$

Where: x, z are two-dimensional coordinates in the elastic infinite half-space Oxz; R_0, R_1, R_2 are the coordinate radii from the observation point to the load positions on the surface; α, β are the angles formed by R_0-R_1 and R_1-R_2 respectively; a, b are the widths of the load edges along the Ox axis; p is the load intensity in terms of force per unit length.

The solution to the problem of distributing additional stress in the elastic infinite half-space subjected to surface loads provides a suitable theoretical basis for studying the influence of the waste dump on the behaviour of the underground support structure. In this study, to minimize the complexity of calculations while ensuring accuracy, a numerical model is built based on the analytical solution of (Gray, 1936) he numerical model developed for the study is shown in Figure 4.

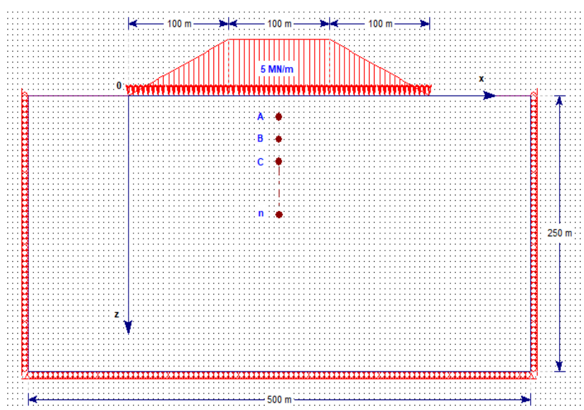

Figure 4. Verification model.

The results of verifying the distribution of additional stresses at the observed point in the elastic infinite half-space using analytical and numerical models are shown in Figure 5. The component stress values (σ_z and σ_x) were collected at observation points located on the axis of symmetry directly below the centre of the waste dump.

From Figure 5, it can be seen that the distribution law and variation trend of the principal stresses (σ_z and σ_x) with depth obtained from the numerical model are completely compatible with the analytical solution. The simulated stress curves closely follow the theoretical values, accurately reflecting the mechanism of load transfer from the surface to the rock mass.

The difference between the numerical simulation and analytical results for σz and σx is only about 2.0%. With negligible structural deviations and a stress distribution trend that matches the theoretical solution, it can be affirmed that the Phase^2 software algorithm and the numerical model constructed accurately reflect the mechanical nature of the problem. Therefore, this model is completely reliable for subsequent parametric analyses of the influence of the waste dump on the roadway support structure. The investigated stresses in Figure 5 were measured at 100 points located on the axis of symmetry of the model. These observation points are spaced 1 m apart, extending from the model surface to a depth of 100 m within the elastic infinite half-space. The stresses σx and σz in the calculation formulas correspond to the major principal stress (σ_1) and the minor principal stress (σ_3) in Phase^2.

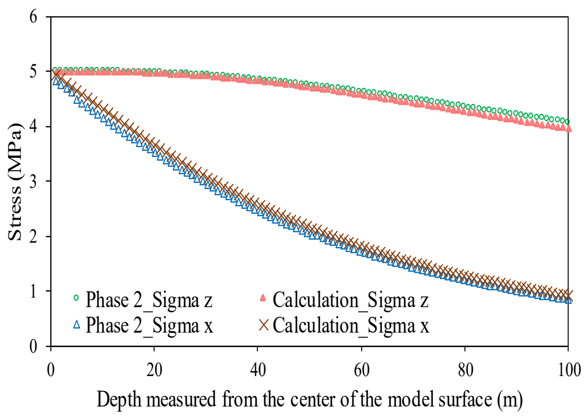

Figure 5. The result comparison between numerical and analytical models.

3. Studying factors affecting internal forces in the roadway structures

3.1. Studying the influence of the volume weight of waste rock

The roadway structure in the simulation scenarios using equivalent plate elements is SVP33 steel, and the parameters of the support structure are shown in Table 2.

Table 2. The parameters of the steel structure SVP33.

Parameter	Symble	Value	Unit
Parameters of U-shaped of the Roadway			
Wall height	h	1.95	m
width	b	5	m
Radius of roadway crown	Rv	2.5	m
SVP33 steel parameters			
Support spacing	l	0.5	m
Section height	-	0.137	m
Cross sectional area	S	0.00425	m^2
Moment inertia	W_x	9.995×10^{-6}	m^4
Young's modulus	E	200000	MPa
Poisson's ratio	μ	0.35	-
Compressive strength	σ_n	500	MPa
Tensile strength	σ_k	500	MPa
Weight per meter	-	33	Kg/m

The objective of this case study is to clarify the influence of the volume weight of waste rock in the waste dump on the moment and normal forces in the U-shaped roadway structure under the waste dump. The scenario of the volume weights of waste rock: $\gamma = 14$ kN/m^3, $\gamma = 16$ kN/m^3, $\gamma = 18$ kN/m^3, $\gamma = 20$ kN/m^3, and $\gamma = 22$ kN/m^3. The height of dump is set at 250m. The distributed force are definded as volume weights of waste rock multiples with height of dump. The distributed force maximum at the peak of dump, reducing to 0 on the ground surface.

The input parameters for the rock mass and support structure models are taken from Tables 1 and 2. The results for moments and normal forces in the steel support structure of the U-shaped under varying volume weight of waste rock are shown in Figures 6 and 7.

The results of the internal force in the roadway support structure in Figures 6 and 7 show that, as the density of the waste rock increases, the moment and normal force in the roadway support structure also increase proportionally. Along the roadway perimeter, the moment always reaches its maximum value at the roadway crown. Meanwhile, the maximum normal force appears at the foot of the roadway wall. The results also show a significant increase in moment mainly at the roadway crown, while the normal force changes significantly at the roadway wall as the density of the waste rock changes.

3.2. Effect of height of the waste dump

The objective of this case study is to elucidate the influence of waste dumping height on the moment and normal force in the support structure of the roadway located at the centre of the waste dump. The roadway is situated at a depth of 50 m below the model surface. In this study, the waste dump height is assumed to increase with the following cases: h = 0 m (no waste dumping), h = 50 m, h = 100 m, h = 150 m, h = 200 m, and h = 250 m. The volume weights of waste rock is set at 20 kN/m^3. Other parameters of the rock mass and support structure are shown in Tables 1 and 2. The results for the moment and normal force in the roadway structure with different waste dumping heights are presented in Figures 8 and 9.

Based on the internal force results from Figures 8 and 9, it can be seen that as the waste dumping height increases, the internal force values in the tunnel support structure below the waste dump also increase. However, the degree and rate of increase of internal forces at different locations along the tunnel perimeter of the support structure differ significantly. Similar to the change in the weight of the waste rock, the maximum moment always reaches its peak at the tunnel roof and changes significantly as the waste dumping height increases, with the axial force changing significantly and reaching its maximum value recorded at the tunnel foot.

4. Conclusions

This study used numerical simulations to systematically investigate the influence of surface waste dumps on the behaviour of roadway structures, through three main groups of factors: the bulk density of the dumped rock, the height of the waste dump development, and the relative position between the roadway and the waste dump. Based on the analysis of moments and normal forces for a U-shaped typical with a straight wall and semicircular arch structure currently applied in the Quang Ninh mining area, the results obtained allow us to draw the following conclusions:

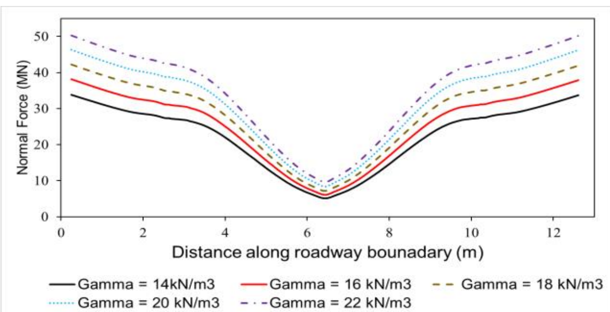

Figure 6. Effect of volume weight of waste rock on normal forces in the roadway structure.

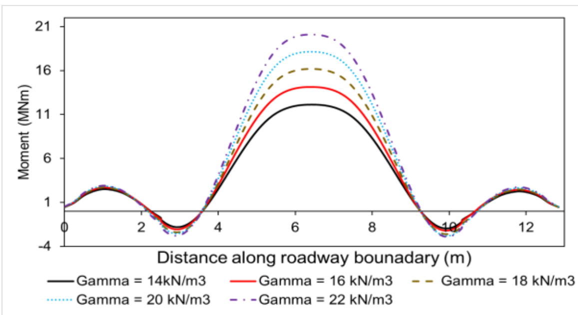

Figure 7. Effect of volume weight of waste rock on moment in the roadway structure.

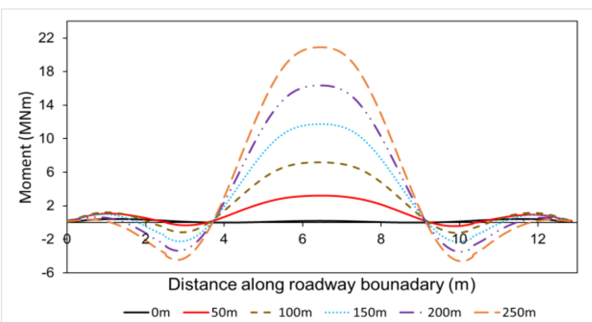

Figure 8. Effect of waste dump height on moment in the roadway structure.

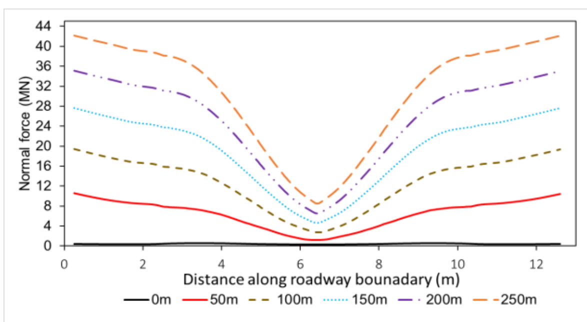

Figure 9. Effect of waste dump height on normal forces in the roadway structure.

Firstly, the bulk density of the dumped rock is a parameter that directly influences the magnitude of internal forces in the roadway structure. As the density of the waste dump increases, both the moment and normal force in the support structure increase according to a clear and consistent pattern, regardless of the roadway's shape.

Secondly, the waste dump height - through its increase over time - influences the development of internal forces in the support structure through an accumulation mechanism. The results show that the moment increases rapidly and is most sensitive to the height of the waste dump, especially for U-shaped support structures, while the normal force increases relatively steadily and reflects the overall compressive state.

These scientific results and arguments are an important basis for selecting unfavourable calculation cases, proposing solutions for rational roadway layout, and guiding the reinforcement of support structures under conditions of surface waste dumps.

Contributions of authors

Sa Huu Nguyen: software, data curation, writing - original draft preparation, visualization, investigation; Doan Viet Dao: conceptualization, methodology, formal analysis ; Kien Van Dang: investigation, writing - reviewing and editing, supervision.

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