

# Research on the Influence of Excavation Seams and Geological Conditions on Surface Movement and Deformation using Geomechanical Digital Models

DANG Van Kien<sup>1</sup>, DO Ngoc Thai<sup>1,\*</sup>, DO Ngoc Anh<sup>1</sup>, NGO Ngoc Thuy<sup>2</sup>, VU Dinh Hung<sup>3</sup>,  
DAO Ngoc Hiep<sup>3</sup>, NGUYEN Huu Sa<sup>1</sup>

<sup>1</sup> Hanoi University of Mining and Geology, 18 Vien street, Hanoi, Vietnam

<sup>2</sup> Military Technical Academy, 236 Hoang Quoc Viet, Hanoi, Vietnam

<sup>3</sup> Mining and Industry consulting joint stock company - VINACOMIN, 565 Nguyen Trai, Thanh Xuan, Hanoi, Vietnam

\* Corresponding author: [dongocthai@humg.edu.vn](mailto:dongocthai@humg.edu.vn)

**Abstract:** Nowadays, the prediction of destruction and subsidence areas due to underground mining is typically carried out using two methods: experimental and phenomenological surveys. The experimental method is based on observational results and experiences from studies of destruction and subsidence in the field. Additionally, reliable experimental or analytical models can be used to forecast destruction and subsidence. Many models have been effectively applied in various countries around the world, especially in Europe. The phenomenon survey is based on the principles of equivalent material models, with the strata of destruction and subsidence mathematically described as ideal materials, adhering to the laws of continuous medium mechanics. However, the equivalent material modeling method has been of limited effectiveness to date, primarily due to the difficulty in describing the complex geological characteristics of the strata, which requires significant costs and time. In the world, there are very few cases of surface structures being located beneath underground mining areas due to good mining planning. In the Quang Ninh underground coal mines, Vietnam, the movement and deformation of the surface in the mine affect the conveyor line in the Northwest II area of Mạo Khê, the G9 Mông Dương mining area, and the -150 MK project area... Therefore, the establishment of geomechanical models combined with field monitoring methods is essential. This paper presents some results of using geomechanical models to study surface movement in underground mines.

**Keywords:** Destruction; subsidence; underground coal mines; the coal storage G9; geomechanical models

## 1. Introduction

Ground settlement, also known as subsidence, occurs when the ground surface lowers due to underground mining activities. Various factors, including the extraction of minerals, the collapse of underground cavities, and changes in groundwater levels, can cause this phenomenon. The extent of settlement can vary significantly depending on factors like the type of mining, geological conditions, and proximity to structures.

Over the past few decades, several researchers have investigated ground surface settlement due to ground loss using various approaches. An empirical formula for the prediction of surface settlement was proposed firstly by Peck (1969) based on the field monitoring data (Figs. 1 & 2). The settlement of a certain point at the ground surface was denoted as follow:

$$S_v = S_{v,max} \cdot e^{-\frac{x^2}{2i^2}} \quad (1)$$

where  $x$  represents the distance from the tunnel centerline, and  $S_{max}$  and  $i$  are the maximum settlement and settlement trough width, respectively.

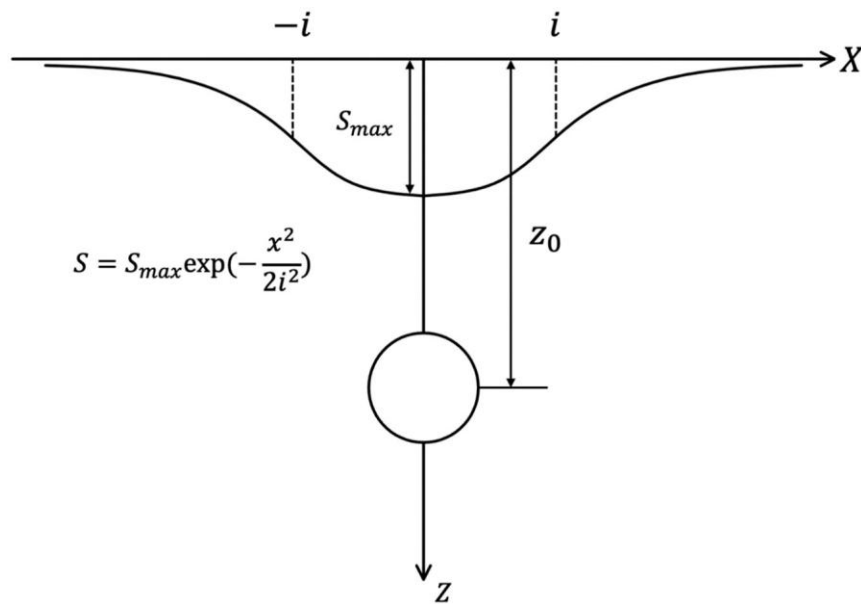


**Fig. 1.** Settlement trough by tunnel excavation

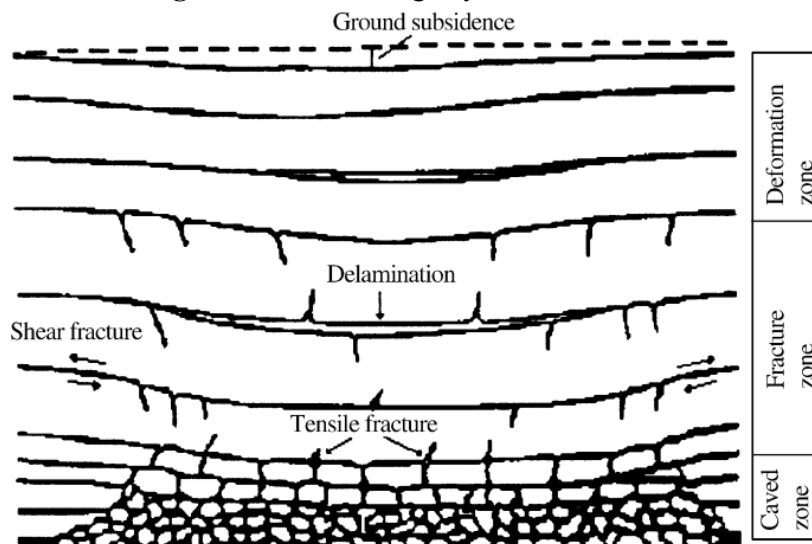


**Fig. 2.** Rock fracture pattern associated with longwall coal mining, in the roof and floor strata near the working face, looking along the longwall panel (Kelly et al., 2002)

Due to the lack of a theoretical basis for the empirical formula, analytical solutions to predict surface settlement induced by ground loss in an elastic half plane were deduced by the virtual image technique (Loganathan & Poulos, 1998; Sagaseta, 1987; Verruijt & Booker, 1996), complex variable method (Verruijt, 1997; 1998). In addition, numerical simulation (Oh & Ziegler, 2014) and model test (He et al., 2012) also play important roles in the investigation of influencing factors, reproduction of ground collapse, and evaluation of ground movement. The coal storage is located on an old mine waste dump, so analytical methods are not applicable due to the destruction of the foundation caused by the settlement of the soil and rock in the mine waste dump area.

## 2. Overview of the coal storage G9

The coal storage G9 system was put into operation by the company in 2015. This is the main coal storage, along with synchronized conveyor systems to receive clean coal from units within TKV to supply the Mong Duong 1 and Mong Duong 2 thermal power plant, according to the contracts signed between TKV and the foreign contractor joint venture.

The coal storage G9 has a large area that can hold over 110,000 tons, with an average coal supply for the thermal power plants of about 7 million tons per year, and an average coal throughput via the conveyor system of approximately 19,200 tons per day. The coal storage G9 layout includes closed coal storage, feeding bunkers, conveyor systems, weighing stations, a 35KV transformer station, as well as office areas for several production units, repair workshops, and electronic weighing systems. During operation,

the use of the coal storage G9 has led to subsidence issues affecting the production of certain construction items, which the Cam Pha Port and Transport Company - Vinacomin has implemented solutions to address the subsidence of the structures at the site. Currently, in the southeastern area of the G9 coal storage, adjacent to the underground area, many cracks, subsidence, and signs of expansion continue to appear. The concrete wall of the coal storage (the end of coal storage number 1) has also cracked significantly; behind coal storage number 2, a crack extending up to 90 meters has appeared, along with the phenomenon of heaving subsidence damaging surface drainage structures and the yard area (Fig. 3). The supporting structure of the conveyor frame and the transfer station has deformed and tilted. The end of coal storage number 1 has cracked reinforced concrete walls, the concrete yard has cracked and heaved, surface drainage ditches are damaged, and the stone retaining wall is also damaged... These phenomena pose a serious safety risk to the structural integrity of the facilities and require urgent assessment and evaluation. Initial assessment results show that the causes of the destruction of the structures on the surface of the G9 coal warehouse include mining activities of the coal seams below, geological conditions, especially the layer of mine waste dump that has not been completely moved, the self-respecting of surface structures, and the dynamic loads of the conveyor belt above.



**Fig. 3.** The destruction of the coal storage G9, Mong Duong coal area, Quang Ninh province

### 3. Deformed state of the coal storage

In this case study, the weight of the coal storage affects the foundation of the coal storage G9. The structural weight of the coal storage G9 has been declared based on the structural plate weight of the frame columns and the roof beams of the coal storage G9. The volume of coal in the coal storage G9 is calculated as follows:  $\gamma_{\text{coal}} = 1.3 \text{ T/m}^3$  with the dimensions of the coal storage G9, the weight of the coal in the coal storage G9. G9 is calculated as  $G_{\text{coal}} = \gamma_{\text{coal}} \times H_{\text{warehouse}} \times B_{\text{warehouse}} \times 1 = 1.3 \times 20 \times 45 \times 1 = 1170 \text{ T}$ , where:  $H_{\text{warehouse}}$  - the height of the coal storage G9,  $H_{\text{warehouse}} = 20\text{m}$ ,  $B_{\text{warehouse}}$  - the width of the coal storage G9,  $B_{\text{warehouse}} = 45\text{m}$ ; 1 - represents the weight of coal in 1 meter length of the coal storage G9. The weight of the coal stored in the coal storage G9 acting downwards on the coal storage G9 foundation is converted into a uniformly distributed load per meter length and used in the model. The load of the conveyor belt in the coal storage G9, calculated for 1 meter of conveyor length, is converted to a concentrated force of 1.3 tons and is used in the model. The study developed a simulation model through cross-section B-B, as shown in Figures 2 & 3. At cross-section B-B, the layers of soil and rock include: the near-surface soil and rock layer that has been previously reinforced by grouting; the fill material layer; and the interleaved layers of cemented clay, seams, and siltstone. The foundation structure of the coal storage G9 has been deformed because it is placed on the ground of an old mine waste dump, which consists of unstable soil and rock such as Figure 4. The image of some distorted points at the coal storage G9 is shown in the Figure 5. The

foundation solution for the coal storage G9 is based on geological layers consisting of previously reinforced soil and rock through cement grouting, mine waste dump layers, cemented clay, siltstone, and coal seams interspersed as shown in cross-section B-B (Figs. 4 & 5). The coal seams includes the upper tunnel system at levels -230-190-N5-CD; upper tunnel at levels -250-180-N5-2CD; upper tunnel TG at levels -250-170-N5-C is the causes of surface subsidence.



**Fig. 4.** Section B-B on the current map of the G9 coal storage

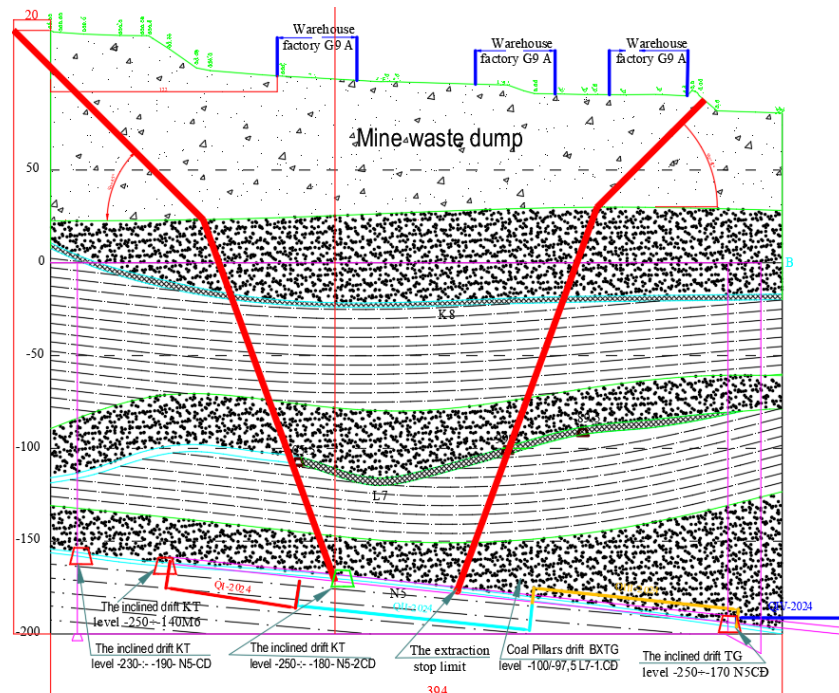


**Fig. 5.** Longitudinal section B-B (From Fig. 4)

Comparing with the monitoring results of the impact of underground mining as a basis for proposing solutions for ground treatment and surface structures. According to the results of the inclinometer displacement monitoring in the report on horizontal displacement monitoring for Cycle 1 and Cycle 2, the positions in the horizontal displacement report include (Minh Anh CO., LTD, 2024) (Tab. 1).

According to the results of the Technical Monitoring Report on the dynamic subsidence in the area of the G9 coal storage yard - Cam Pha Port and Transport Company - Vinacomin, the maximum subsidence value is -93mm (benchmark CT121), -88mm (benchmark CT122), -78mm (benchmark CT123) (Area of the conveyor supports in the coal storage G9 number 1). According to the deformation analysis results, the

subsidence of the coal storage G9 area using the numerical modeling method at section B-B through the coal storage G9 has a maximum vertical displacement value of 364.0 mm.

**Tab. 1.** Horizontal displacement monitoring at the coal storage G9 location

| Location                                                            | The location of the largest horizontal displacement | The value of the largest horizontal displacement | Displacement rate mm/month |
|---------------------------------------------------------------------|-----------------------------------------------------|--------------------------------------------------|----------------------------|
| Base of conveyor QTS.G9-1.<br>Surveyed at a depth of -0.5 to -70.5m | -2.0 m                                              | 16.58mm                                          | -6.63                      |
| QTS.G9-2 operating yard<br>Surveyed at a depth of -0.5 to -70.5m    | -1.0 m                                              | 5.1mm                                            | -2.04                      |

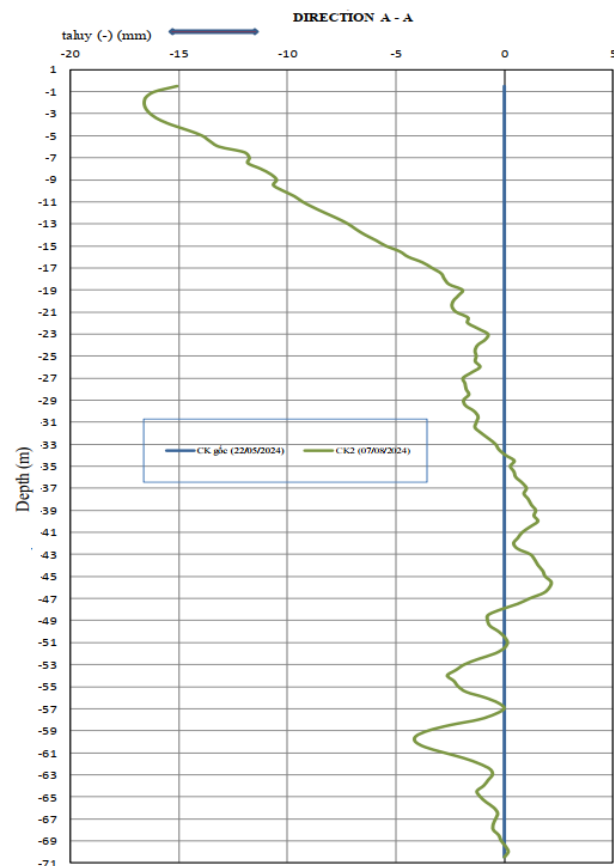


**Fig. 9.** Horizontal displacement monitoring at foundation of the coal storage G9

## 4. Numerical modelling

### 4.1. Dimension of model

In a FEM analysis, the model's boundaries are determined to avoid any distortion and wrong calculation. It should be large enough to ignore all boundary effects on the model and the modelling results. The boundary's horizontal side was 300 m, and the boundary's vertical side was 500m. The geological and geotechnical data of a similar project were utilised. The obtained results were analysed and discussed to understand the mechanical behaviour of the parking structure and its surrounding soil. The effect of the geotechnical characteristics of the surrounding soil on the construction was proven. In a FEM analysis, the model's boundaries are determined to avoid any distortion and wrong calculation. In this research, the displacements must not exceed 1mm. The model is set at [-300:300] in the horizontal axis and [0:-500] in the vertical axis. The numerical model comprises the linked triangle elements, and each triangle is divided into nodes. When the model is loaded, the model's geometry is moved, and the modelling accuracy depends on the model's node number. In the scope of this paper, a 6-node model is built. This setting avoids the high time consumption calculations while providing reasonable accuracy for the modelling results.

### 4.2. Material failure criteria and boundary condition

The model has dimensions including a height of 300m and a width of 500m. The left and right boundaries of the model are fixed horizontally with zero horizontal displacement at the boundaries; vertical

displacement is free. The bottom boundary of the model has both horizontal and vertical displacements equal to zero. The surface boundary is free, allowing for vertical and horizontal displacements, with the positions of the soil layers, the two warehouses, and the Bunke illustrated as shown in Figure 6.

The reinforced concrete structure of the Bunke and the coal storage G9 uses an elastic model. The structural frame of the coal storage G9 is simulated according to the structural diagram, with the column legs fixed and the loads transmitted down through the columns to the foundation. The upper structural frame consists of columns, roof beams, and foundation concrete, which are simulated using plate elements with technical specifications as shown in Table 2. The structures for the drilled holes for grounding use node-to-node anchor elements with technical specifications as shown in Table 2, and the technical specifications for the injection pump hole as shown in Table 3. The soil and rock layers are utilized according to the Mohr-Coulomb failure criteria, with the soil parameters used as in Table 4. Construction works are shown in Table 5. The simulation diagram is shown in Figure 6.

**Tab. 2.** Mechanical parameters of reinforced concrete shell, concrete tunnel for the coal storage G9 flooring, the coal storage G9 structure, and barrette retaining wall

| Parameters                 | Unit                 | Reinforced concrete shell for walls and roof of the bunker and tunnel. | Reinforced concrete shell for walls and floors of bunkers and tunnels | Concrete floor slab for the coal storage | Structural frame columns and roof beams for the coal storage H1300 | Structural frame columns of the coal storage 1500 | Retaining walls barrette |
|----------------------------|----------------------|------------------------------------------------------------------------|-----------------------------------------------------------------------|------------------------------------------|--------------------------------------------------------------------|---------------------------------------------------|--------------------------|
| Thickness, m               | m                    | 0.3                                                                    | 0.4                                                                   | 0.15                                     | -                                                                  | -                                                 | 0.6                      |
| Poisson coefficient, $\nu$ | -                    | 0.2                                                                    | 0.2                                                                   | 0.2                                      | 0.15                                                               | 0.15                                              | 0.2                      |
| Compressive strength, EI   | kN/m                 | $7.875 \times 10^6$                                                    | $18.66 \times 10^3$                                                   | 8437.5                                   | $265.8 \times 10^3$                                                | $186.7 \times 10^3$                               | $540 \times 10^3$        |
| Bending stiffness, EA      | kN.m <sup>2</sup> /m | $10.5 \times 10^6$                                                     | $14.0 \times 10^6$                                                    | $45 \times 10^5$                         | $15.75 \times 10^6$                                                | $14 \times 10^6$                                  | $18 \times 10^6$         |
| Weight, w                  | kN/m/m               | 9.6                                                                    | 9.6                                                                   | 7.5                                      | 11.25                                                              | 10                                                | 14.4                     |

**Tab. 3.** Technical specifications for the injection pump hole

| No       | Symbol | Value | Unit |
|----------|--------|-------|------|
| Diameter | D      | 105   | mm   |
| Length   | L      | 9     | m    |

**Tab. 4.** Mechanical parameters of coal and rock

| Type of rock                           | Compressive strength, $R_c$ (MPa) | Tensile strength, $R_t$ (MPa) | Young's modulus, $E$ (GPa) | Poisson's ratio, $\nu$ | Cohesion $c$ (MPa) | Friction angle, $\phi$ (o) | Density, $\gamma$ (kg/m <sup>3</sup> ) |
|----------------------------------------|-----------------------------------|-------------------------------|----------------------------|------------------------|--------------------|----------------------------|----------------------------------------|
| Conglomerate, coarse grained sandstone | 102.6                             | 7.8                           | 16.8                       | 0.25                   | 18.7               | 33                         | 2580                                   |
| Sandstone                              | 92.0                              | 10.5                          | 18.7                       | 0.25                   | 30.2               | 30                         | 2620                                   |
| Mudstone                               | 46.7                              | 5.5                           | 8.6                        | 0.25                   | 12.2               | 29                         | 2600                                   |
| Claystone                              | 20.0                              | 1.8                           | 3.7                        | 0.25                   | 4.8                | 32                         | 2640                                   |
| Coal                                   | 15.0                              | 1.2                           | 3.4                        | 0.25                   | 2.1                | 27                         | 2460                                   |

**Tab. 5.** Construction works

| Phase number | Construction works                                                                                     |
|--------------|--------------------------------------------------------------------------------------------------------|
| Phase 1      | Establishing initial parameters and setting boundary conditions.                                       |
| Phase 2      | Reduce the modulus of the rock mass in the area of the drifts being excavated                          |
| Phase 3      | Constructing 02 the coal storage G9 and setting up the injection boreholes on the coal storage G9 site |
| Phase 4      | Excavating the bunker and installing the reinforced concrete bunker shell                              |
| Phase 5      | Run the model with the material model of coal/rock.                                                    |
| Phase 6      | Analyze and evaluate the results of the model.                                                         |

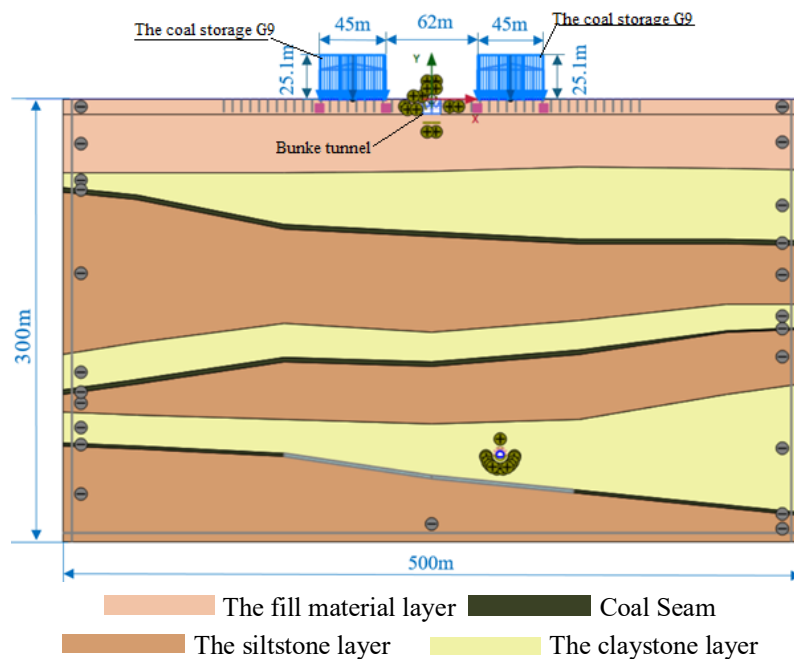


**Fig. 6.** The diagram simulates the phenomenon of deformation and subsidence causing damage to the completed construction items on the coal storage G9 area

Calculate the level of impact according to the model and compare it with the theoretical calculations of the impact of underground mining as a basis for proposing solutions for site treatment and surface structures. The results of the deformation and subsidence calculations for the coal storage G9 ground according to the model are shown in Figure 7. The phenomenon of subsidence in the coal storage G9 foundation before reinforcement is shown in Figure 8.

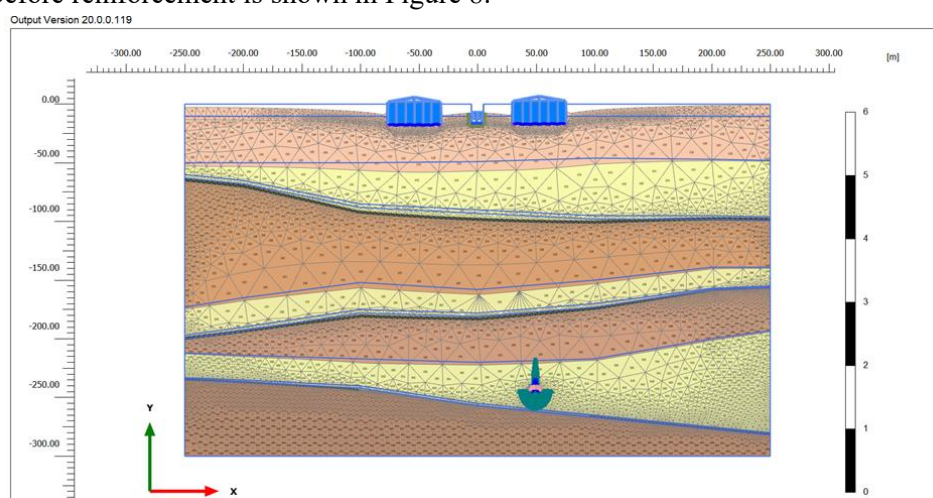


**Fig. 7.** Results of ground displacement and subsidence before reinforcement

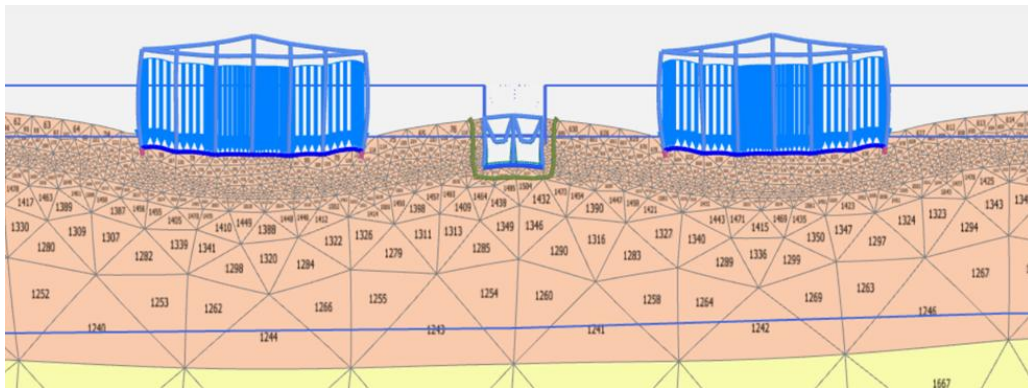


**Fig. 8.** The phenomenon of subsidence in the coal storage G9 foundation before reinforcement

#### 4.3. Layout of G9 coal storage

In this model, the G9 coal storage area includes: 2 coal storages and an underground bunker tunnel, along with the proposed reinforcement solutions. The model diagram is shown in Figure 9, and the simulation results are presented in Figures 10 and 11.

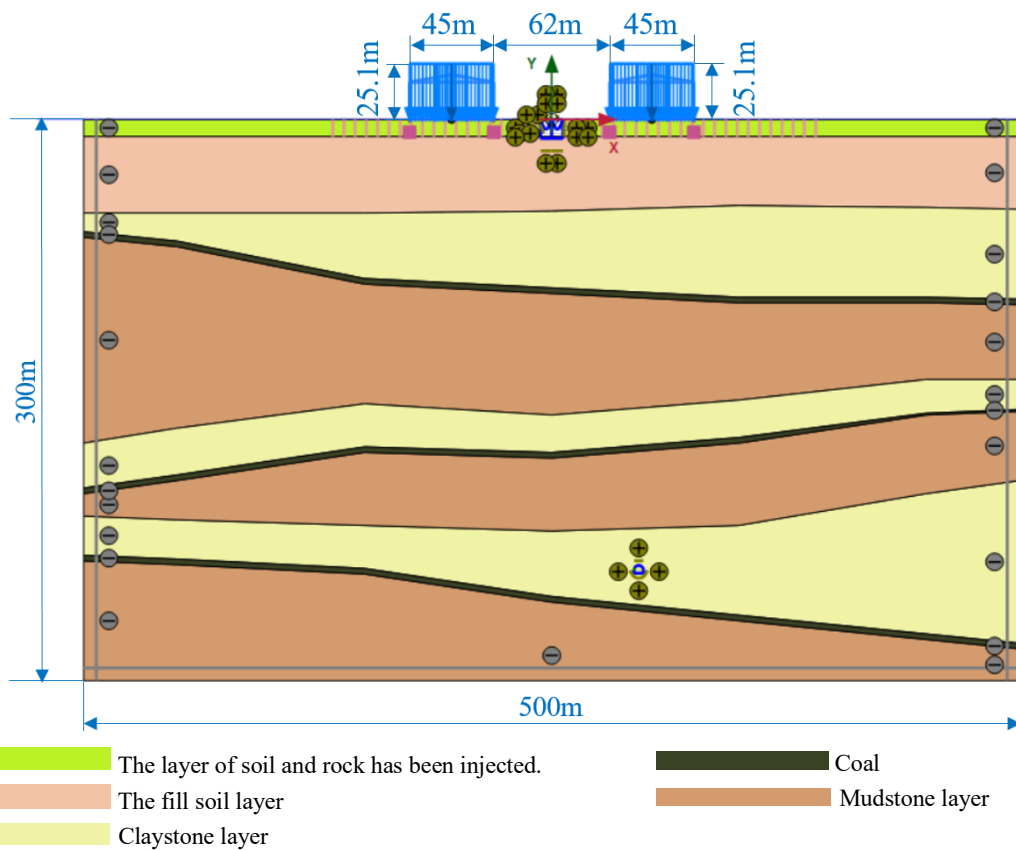


**Fig. 9.** The phenomenon of subsidence in the coal storage G9 foundation before reinforcement

The results of the numerical simulation show that the maximum displacement and ground subsidence value is 18.4mm, and the location where the largest ground displacement and subsidence occurs is at the foundation of the coal storage G9. Thus, when using the reinforcement solution, the displacement and subsidence value of the coal storage G9 at the Bunke location has decreased from 364.0mm to 18.49mm. The distribution of internal forces and displacements of the barrette retaining wall at the Bunke location is illustrated in the Figures 10 and 11 as follows.

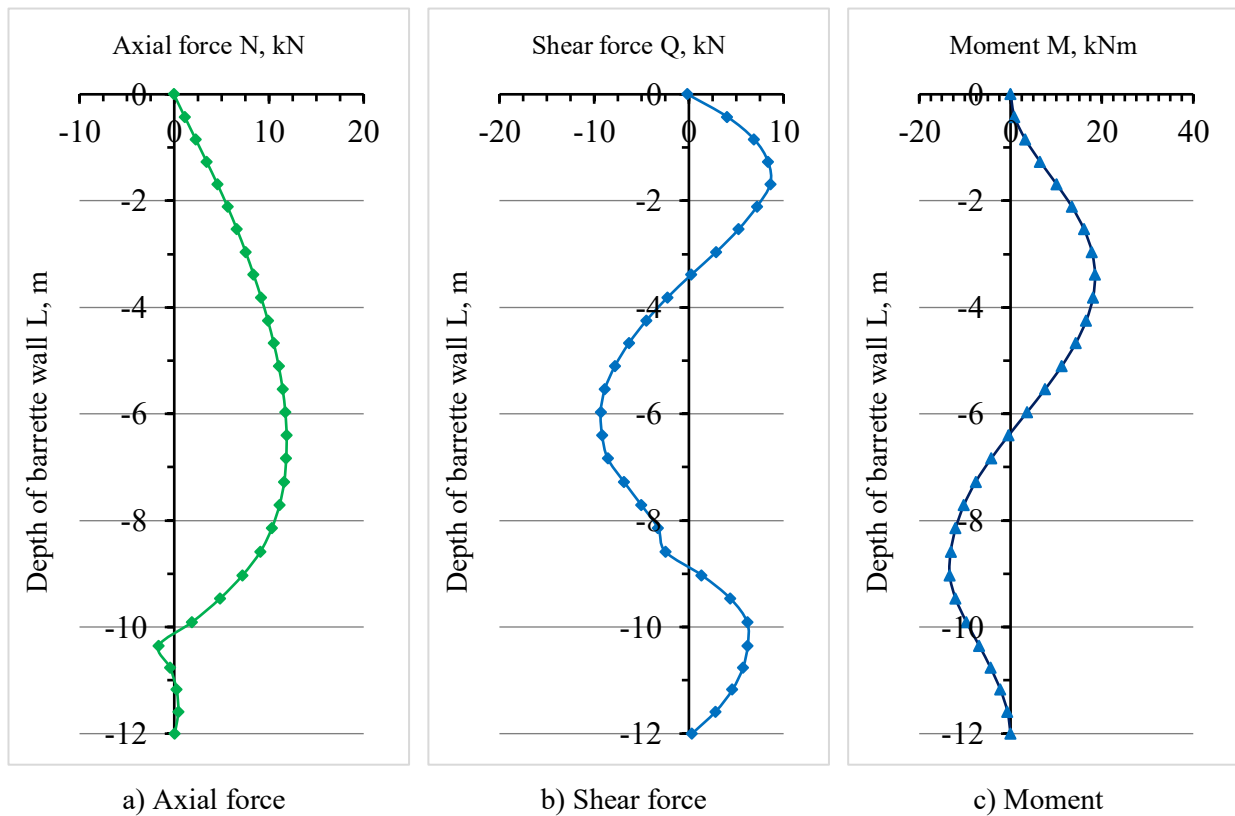


**Fig. 10.** Distribution of internal forces in the barrette wall at the location of the bunke

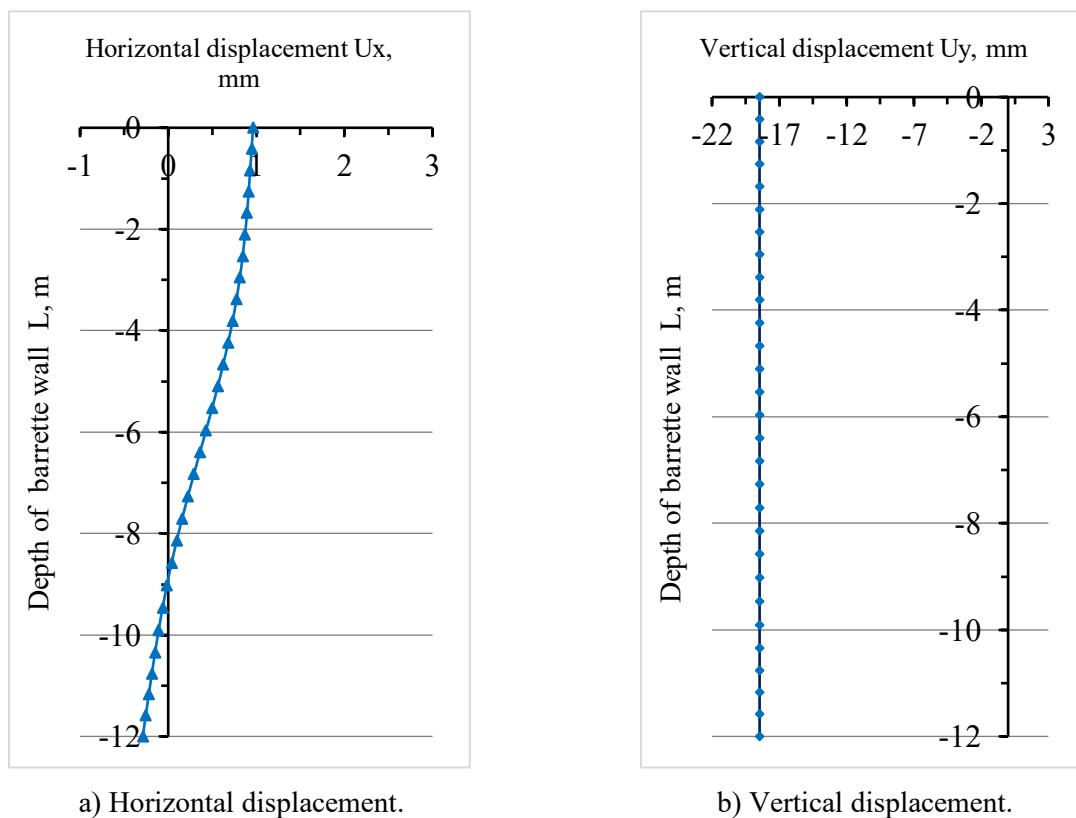


**Fig. 11.** Displacement of the barrette retaining wall at the bunke location

The results of the numerical simulation show that the maximum ground displacement and subsidence value is 0.3640m (364.0mm), and the location where the maximum ground displacement and subsidence occur is at the foundation of the coal storage G9.

## 5. Calculate and check vertical displacement, subsidence, and propose solutions to enhance stability for the underground components of the construction items

Proposed reinforcement solutions: The coal storage area and the underground bunker tunnel. Based on the results of deformation calculations and ground subsidence of the coal storage G9 using numerical simulation methods, along with the comparison of results from dynamic measurement methods in the field, the study proposes the following reinforcement solutions:

+ On the surface of the coal storage G9, the method of grouting cement is used with drill holes with a diameter of D105, L 9m, and the distance between the drill holes is  $l = 3 \times 3$  m. At the position far from the area of the two coal storages, the method of grouting cement is used with drill holes with a diameter of D105, L=6m, and the distance between the drill holes is  $l = 3 \times 3$ , as shown in Figure 12.

+ Along the underground bunker tunnel, the barrette wall is used with a wall depth of  $LB = 12$  m and a wall thickness of  $dB = 0.6$  m to increase stability and reduce the occurrence of settlement deformation for the underground bunker tunnel line (Fig. 13). Simulation diagram of the underground bunker on the model is presented on Figures 14 and 15. The phenomenon of displacement and subsidence of the coal storage G9 floor at the underground bunker tunnel location is presented on Figure 16. The results of the numerical simulation show that the maximum displacement value and subsidence of the coal storage G9 floor at the underground bunker tunnel location with vertical displacement is 367.3mm before using the reinforcement solution. By using the reinforcement solution, the displacement and settlement value of the coal storage G9 floor at the underground tunnel location with a vertical displacement of 18.58mm is observed. The distribution of internal forces and displacements of the barrette retaining wall at the underground tunnel location is shown in Figures 17 and 18 as follows.

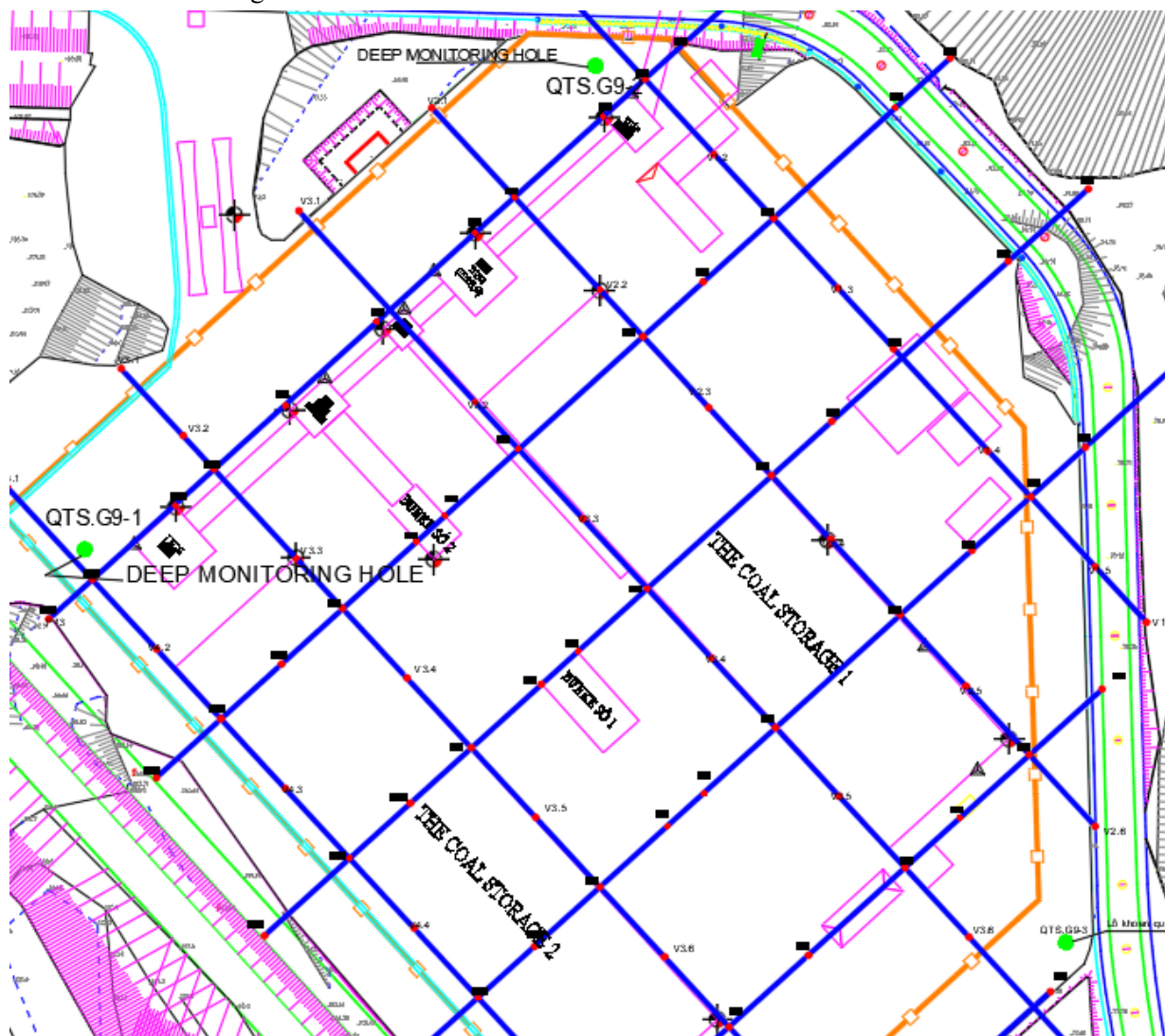


Fig. 12. Reinforcement diagram the coal storage G9 by grouting cement method

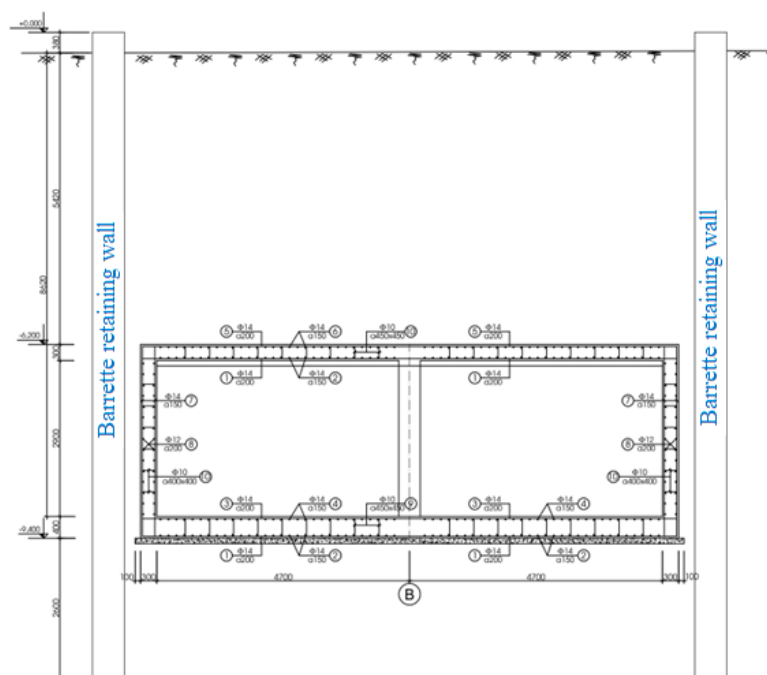


**Fig. 13.** Reinforcement solution for underground bunker using barrette diaphragm wall

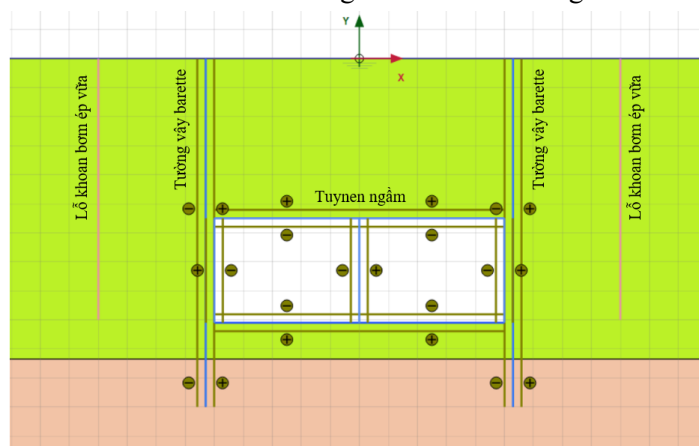


**Fig. 14.** Simulation diagram of the underground bunker on the model

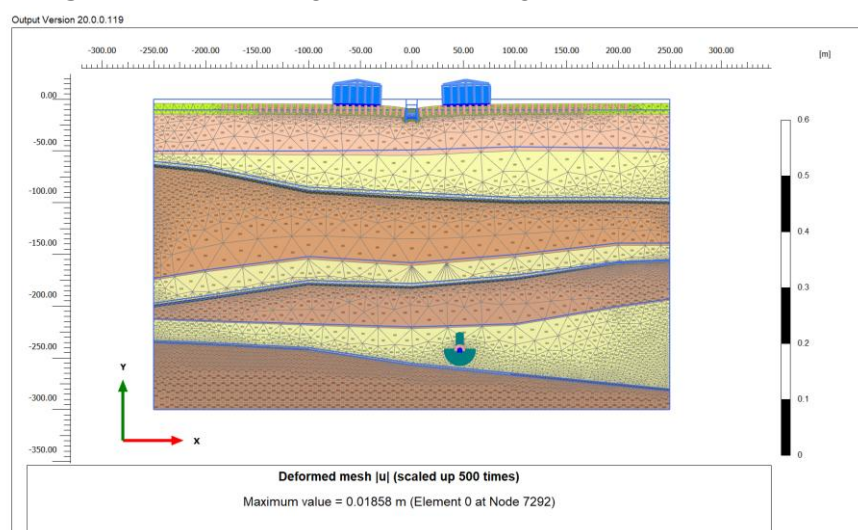


**Fig. 15.** Results of displacement and subsidence of the coal storage G9 floor during applying reinforcement solutions for the floor of the coal storage G9 and the wall of underground bunker tunnel

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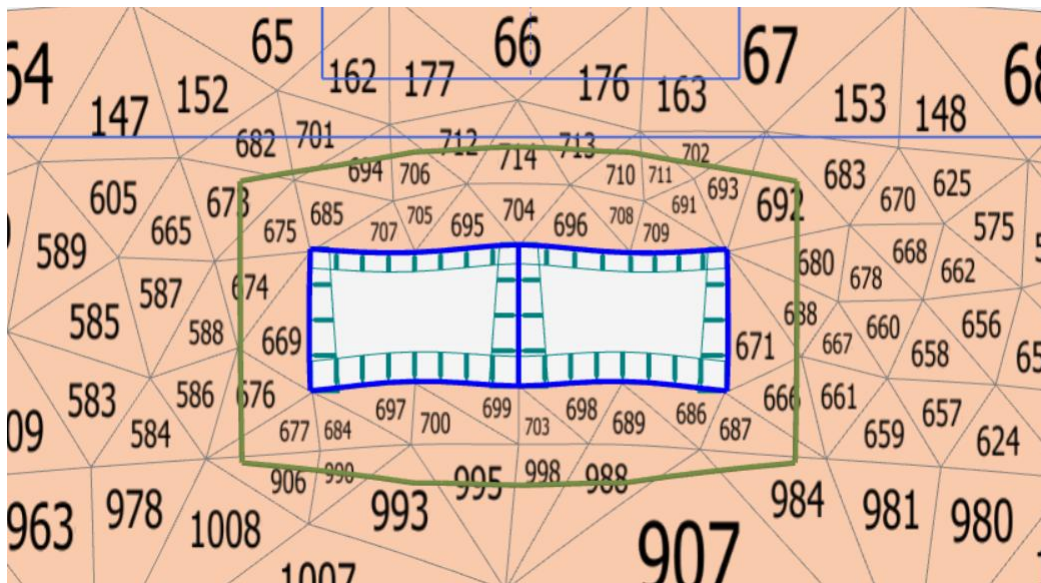


**Fig. 16.** The phenomenon of displacement and subsidence of the coal storage G9 floor at the underground tunnel location

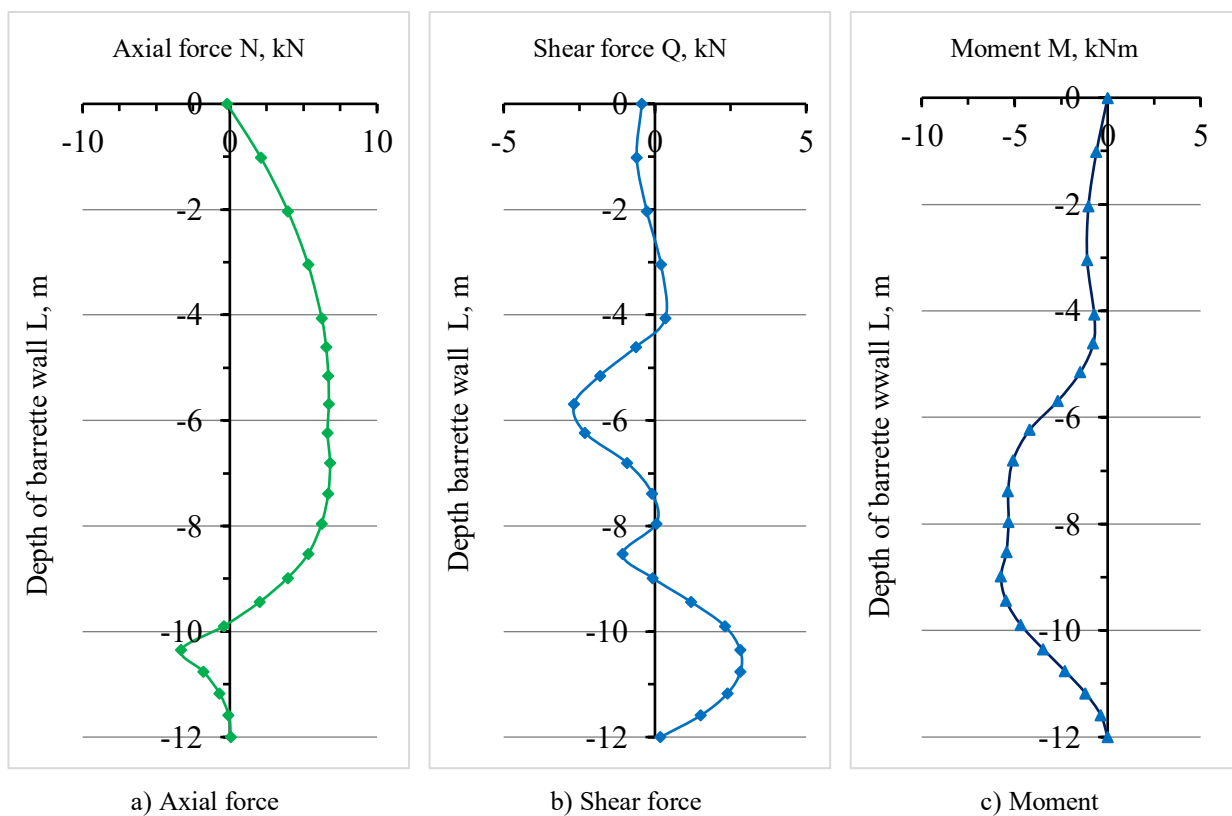


**Fig. 17.** Distribution of internal forces in barrette retaining walls at the bunk location

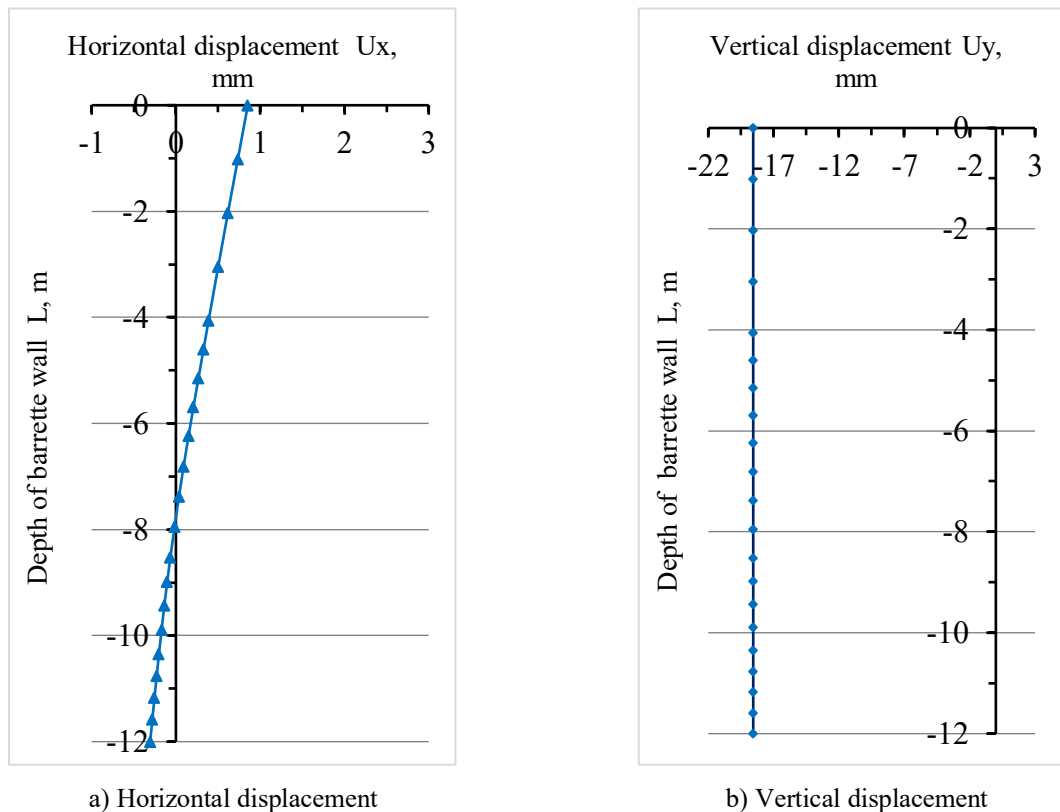


**Fig. 18.** Displacement of the barrette diaphragm wall at the underground tunnel location

The displacement results in Figure 19 show that the maximum horizontal displacement occurs at the surface with a value of 9 mm. The vertical displacement is 19 mm. These displacement values are small, indicating that the retaining wall solution effectively limits the horizontal movement of soil and rock particles into the tunnel void, thereby reducing the lateral pressure exerted on the tunnel walls.

## 6. Conclusion

The research results of the paper show that the cause of the destruction of the structures on the surface of the coal storage G9 is due to the exploitation of the coal seams below, geological conditions, especially the layer of mine waste rock that has not been completely moved, the self-respecting of surface structures, and the dynamic loads of the conveyor belt above. The article presents a geomechanical model simulating the reinforcement results of the coal storage G9 in the Mong Duong area, which has experienced subsidence due to being located on an old mine waste dump site. Based on the Mohr-Coulomb model, numerical simulation tests were carried out on the failure law of overlying strata by using the command flow, and the influence of mining of the lower 1 and excavation of coal seams on the overlying strata subsidence and surface penetration were obtained. The simulation results indicate that reinforcing the foundation of the coal storage allows for a reduction in surface subsidence, leading to more stable surface structures. For the underground bunker, the use of a retaining wall system is necessary to reduce horizontal deformation that could damage the bunker walls.

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