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# Numerical approach for designing support systems for underground excavations in serpentinite under squeezing ground conditions: the case of the Bou-Azzer mine, Morocco

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**ABSTRACT**

The instability of underground excavations developed in serpentinite rock masses at the Bou-Azzer cobalt mine in Morocco has long been a critical concern for geotechnical engineering. The challenges encountered in two previous strategic projects, at depths of 360 meters and 510 meters, were mainly attributed to stress conditions exceeding the rock strength, leading to significant reductions in the cross-sectional area of the excavations and severe deformation of the installed support systems. Conventional empirical support design approaches applied at the mine have shown clear limitations when dealing with serpentinite rock masses. Another limitation of these methods is that they do not allow for the assessment of support system performance and deformation control to improve the stability of such deep excavations. The primary objective of this study is to develop a reliable support system capable of ensuring a safe working environment for personnel and equipment through numerical modeling of excavation behavior at a depth of 540 meters, corresponding to the new mine extension. The adopted methodology is based on detailed two-dimensional finite element modeling, explicitly accounting for the variability in the mechanical behavior of the serpentinite rock mass and its interaction with the proposed support systems through a site-specific analysis. Numerical simulations were conducted for different serpentinite types under two analysis scenarios: excavations during development and excavations with installed support. The results indicate that maximum displacements are critically high in type 4 serpentinite and remain substantial in type 1 serpentinite. By contrast, moderate displacement values were observed in type 2 and type 3 serpentinites. However, once the proposed support measures were implemented, the maximum displacements were reduced to acceptable limits with respect to the excavation span and height, and the safety factors improved to between 1.10 and 1.30 for the crown and from 1.10 to 1.60 for the sidewall. Numerical modeling has proven to be an effective decision-support tool for deep underground excavations in complex rock conditions. The findings of this study provide a practical and reliable basis for designing support systems in deep mining environments, with approaches that can be extended to other sites facing similar geotechnical challenges.

**Keywords:** *Underground mining, Serpentinite, Squeezing ground, Numerical modeling, Support system..*

## 1. Introduction

Many underground mines worldwide face significant challenges at great depth in maintaining the stability and functionality of their excavations under squeezing ground conditions. The design of support systems for underground openings in the serpentinite formations of the Bou-Azzer mine represents a major geotechnical stability challenge, particularly beyond depths of 360 m. This complexity arises from the high compressive stress conditions characteristic of serpentinite rock masses, as documented at various depths in a previous study [1].

Such ground instabilities, associated with high in situ stress conditions, impose considerable technical and economic constraints while also causing substantial delays in excavation and support installation. These disruptions directly affect the cobalt ore extraction process, especially in areas where excavations intersect serpentinite formations. This is particularly the case in the study area, at the two main levels located at 360 m and 510 m depth, which serve as strategic drifts for personnel access and material transport, including both waste rock and ore (Figure 1). The Bou-Azzer East region, which hosts the largest cobalt orebody in terms of tonnage and average grade within the Bou-Azzer mine, is especially affected by these problems.

The ground instabilities observed in the Bou-Azzer East region do not manifest as block falls or structurally controlled block slides but rather as large-scale rock mass failures. These phenomena are primarily driven by induced stresses exceeding the strength of the rock, leading to significant reductions in the cross-sectional area of underground excavations. The issue of squeezing ground conditions in underground mines has been the subject of extensive research [1–5]. The lack of

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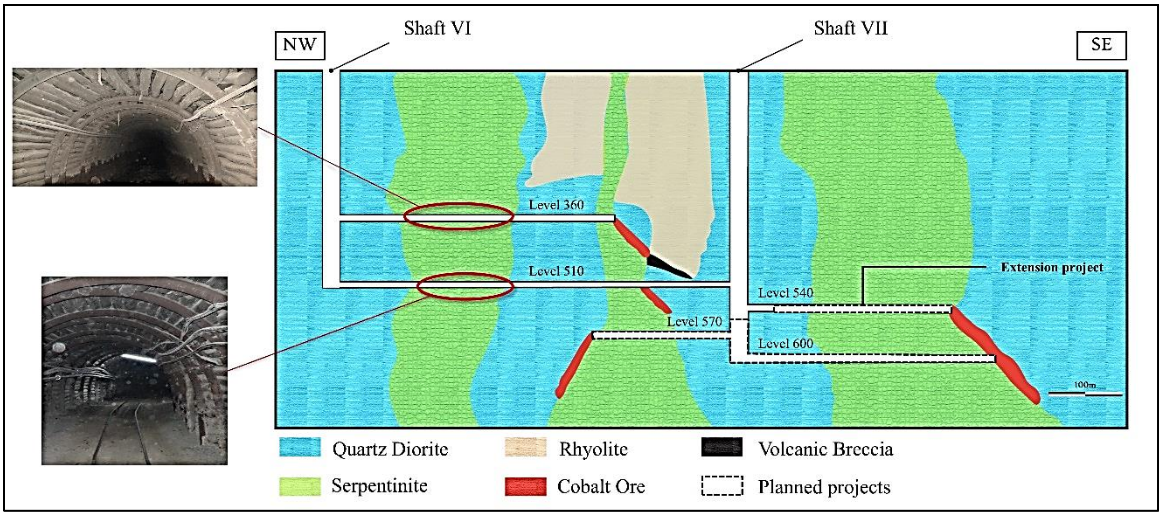


**Figure 1.** Location of the 360 m and 510 m levels in the Bou-Azzer East zone as well as the new Shaft VII project.

scientific research dedicated to understanding the behavior of underground mining excavations in rock masses of low to very low geomechanical quality (particularly in serpentinite formations) remains a major limitation in the field. In fact, serpentinite exhibits an intrinsically complex nature, characterized by strong heterogeneity in its mechanical, geological, and behavioral properties.

The design of ground support systems still largely relies on empirical approaches derived from geomechanical classifications and operational experience [6–9]. While these methods are effective and practical under moderate geological conditions, they show significant limitations when applied to deep underground mining excavations subjected to high stress levels and hosted in weak rock masses or tectonically complex settings. Indeed, such approaches are based on simplifying assumptions that do not explicitly account for the evolution of in situ stresse, the non-linear behavior of the rock mass, or the progressive deformation mechanisms observed at great depth.

A recent study by examined the application of empirical classification systems for support design in underground excavations within low-quality serpentinite rock masses at a depth of 460 m in the Bou-Azzer mine [10]. The results highlighted the limitations of empirical classification methods and demonstrated the need for more appropriate approaches and advanced techniques, such as numerical modeling.

At the Bou-Azzer mine, support design approaches have relied mainly on these empirical methods and past operational experience. They have shown their limitations at greater depths. Under such conditions, the increasing influence of tectonic stresses complicates the selection of reliable and effective support systems, particularly in serpentinite rock masses of poor to very poor geomechanical quality.

Numerical modeling is therefore an essential tool for simulating the behavior of rock masses through mathematical equations based on analytical formulations or algorithms [11]. Most numerical analyses in geotechnical engineering problems involve the use of computers to solve large sets of equations simultaneously using iterative techniques. For this reason, numerical analysis is often referred to as mathematical modeling and represents a powerful form of analytical investigation [11].

Extensive research has been devoted to the application of numerical modeling in geotechnical engineering for underground mines. This approach makes it possible to assess stress states and deformations virtually at any point within the rock mass, while accounting for geological heterogeneities [12–19]. Furthermore, several studies have specifically investigated the use of numerical modeling to mitigate the effects of convergence in squeezing ground conditions [20–22].

The design of support systems for underground excavations in the serpentinite formations of the Bou-Azzer East region, using numerical models, offers the advantage of assessing the distribution of stresses and displacements within the serpentinite rock mass, as well as the response of different types of installed support. The support types currently recommended are based on empirical methods and operational experience with support systems such as steel sets, timber, and shotcrete, particularly for underground excavations developed in serpentinite rock masses above 500 m in depth. Achieving efficient ore recovery requires solutions that ensure long-term operational durability and technical feasibility while providing a safe working environment for miners in terms of geotechnical stability. This paper presents a methodology based on 2D numerical modeling, using finite element software to simulate standard underground excavations. Numerical simulations were carried out for the different serpentinite types under two analysis scenarios: Phase 1 corresponds to excavations during development, while Phase 2 considers excavations with the implementation of the recommended support. The aim of the study is to quantify the deformation control capacity of the proposed support systems in serpentinite and to develop a reliable design for 540 m deep conditions, ensuring excavation stability and safety through the minimization of deformations and displacements under squeezing ground conditions.

## 2. Geological context of the study area

The Bou-Azzer mine, located in the western part of the Bou-Azzer–El Graara inlier, lies within the central zone of the Anti-Atlas, in southern Morocco (Figure 2). This inlier is also situated along a NW–SE oriented fault zone that marks the northern boundary of the West African Craton [23]. It is characterized by a Precambrian basement overlain by a Paleozoic cover. Structurally, it consists of a stack of tectonic blocks interpreted as fragments of a Neoproterozoic supra-subduction zone [24, 25].

The Bou-Azzer East study area, also recognized as the main cobalt ore mining zone, is located in the western part of the Bou-Azzer mining district (Figure 3). From a structural perspective, the Bou-Azzer East region is composed of the following principal geological formations:

(i) Gneiss and amphibolitic rocks outcropping in the southwest, often bounded by fault contacts oriented NE–SW;

(ii) Serpentinitized harzburgite terrains and green rocks occupying the central part [28–30];

(iii) A syn-tectonic quartz-diorite massif cropping out in the western part, intruding into the serpentinites.

The serpentinite rock masses of the Bou-Azzer East region are the focus of this study. These rock masses are widely developed throughout the area, occurring in two main forms: NW-trending lenses and NE-

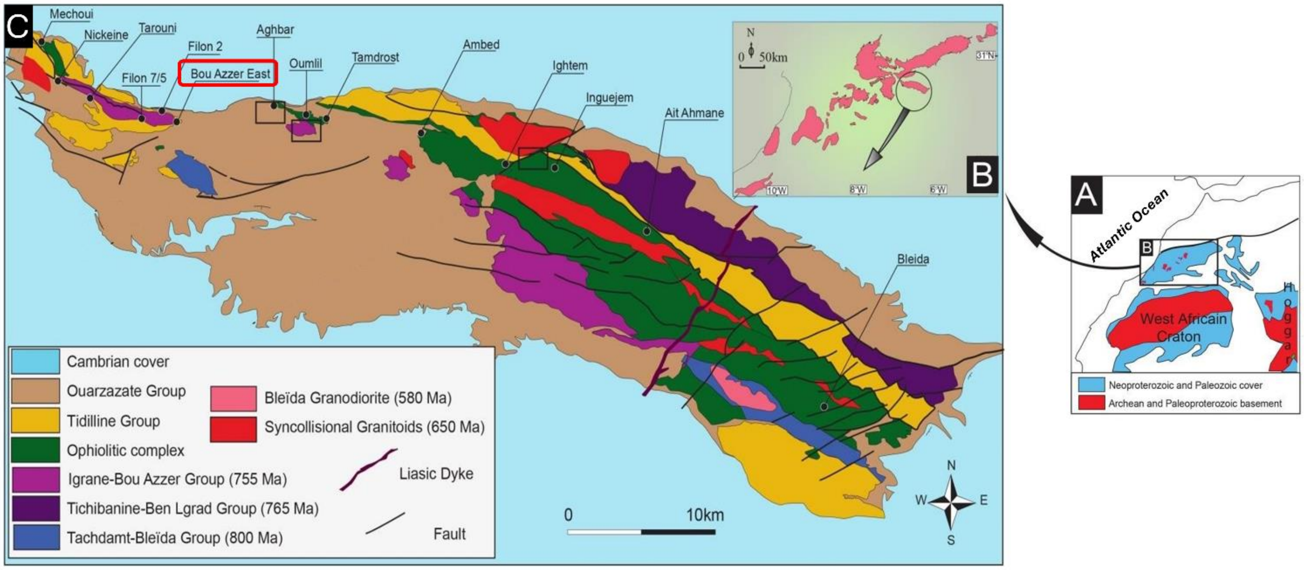


**Figure 2:** Geological setting of the Bou-Azzer mining district within the Anti-Atlas Belt, Morocco. (A) Simplified map of the Anti-Atlas Belt showing the main Precambrian inliers along the northwestern margin of the West African Craton; (B) Location of the Bou-Azzer–El Graara inlier; (C) Geological map of the Bou-Azzer mining district showing the location of the Bou-Azzer East serpentinite sector, modified after [26,27].

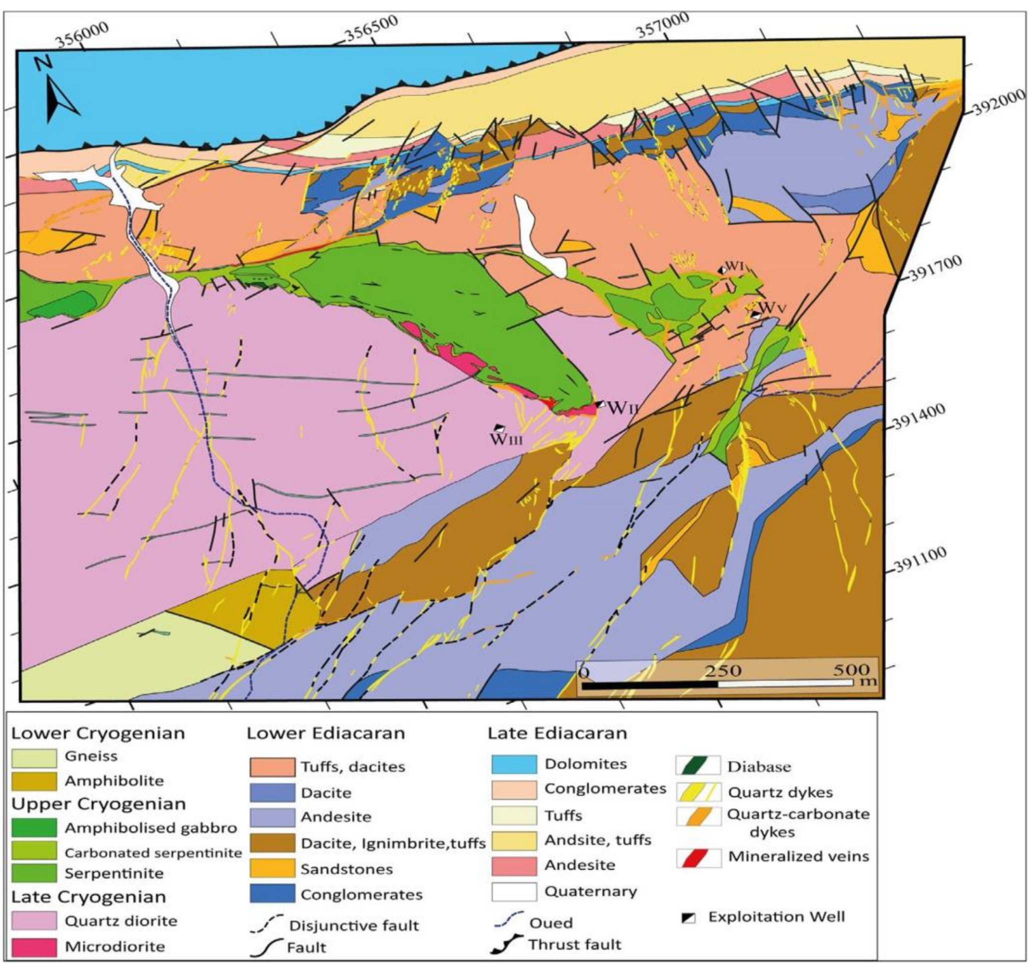


**Figure 3.** Geological map of the Bou-Azzer East deposit [32].

trending branches. At the surface, serpentinites are in tectonic contact, either directly or through quartz–carbonate veins. In the contact zones, serpentinites are affected by ductile deformation, characterized by mylonitic shear zones and C/S-type shear fabrics (composite shear–schistosity structures). They display a range of colors, from light green to dark green and yellowish [31, 32].

The serpentinite rock mass at the Bou-Azzer mine is characterized by horizontal variability at the same depth. Field observations conducted in several sectors, complemented by laboratory geological analyses, reveal the presence of four main facies with distinct geotechnical parameters within this single lithological unit [1]. This variability is attributed to intense hydrothermal alteration (Figure 4).

## 3. Identification of instability forms in serpentinite

According to Hoek and Brown and Hudson [33,34], rock mass failure modes generally result from rock instability and depend on several factors, including the composition of the rock mass, the influence of tectonic stresses and groundwater pressure, and the size of the underground excavation. The commonly identified failure modes include gravity-controlled block falls, shear failures induced by stresses within the rock mass, and swelling in the specific case of water-sensitive minerals.

The behavior of serpentinite rock masses around an underground excavation is strongly influenced by both the degree of fracturing and the induced stresses near the excavation. In the Bou-Azzer East region, serpentinite rock masses exhibit instability below depths of 400 m, driven by induced stresses. In this study, we provide a qualitative description of the mechanisms responsible for instability, using an empirical database specific to the Bou-Azzer mine (compiled from operational experience) together with the characterization of the different failure modes observed in the field. This analysis allows us to broadly identify two main failure modes in serpentinite rock masses beyond 400 m depth:

Rockfalls in the form of blocks and spalling of small rock fragments of varying sizes and shapes, combined with shear failure caused by induced stresses;

Shear failures accompanied by large deformations, together with stress relaxation, which can lead to time-dependent inward convergence of the underground excavation perimeter (squeezing behavior).

### *3.1. Between 360 and 460 meters depth*

Field observations and surveys were carried out on several underground excavations in serpentinite after the installation of steel-set supports with backfilling, at depths ranging from 360 m to 460 m. Rockfalls in the form of blocks, as well as spalling of small rock fragments of various sizes and shapes, were documented. Examination of several blocks and fragments indicated that these results are attributable to the acceleration of occasional shear failure mechanisms induced by stress, combined with gravity-controlled failure of the rock mass (Figure 5).

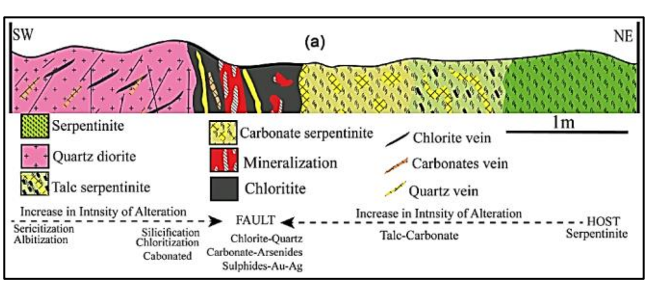


**Figure 4:** Cross-section at a depth of 540 m showing the zoning of hydrothermal alterations within the serpentinite in the Bou-Azzer East zone [32].

### *3.2. Starting from 500 m depth*

#### *3.2.1. Moderate convergence*

In a section of the underground excavation at 510 m depth through the serpentinite rock mass, centimeter-scale deformation of the steel sets was observed, with increased visibility of the timber lagging along the sidewall (Figure 6). After examining the fallen blocks and crushed material present in the excavation walls, together with the results of daily monitoring conducted by field controllers at the Bou-Azzer mine, it was concluded that a shear failure mode, caused by induced stresses due to the low strength of the rock, was occurring in combination with gravity-controlled block falls of various sizes and shapes.

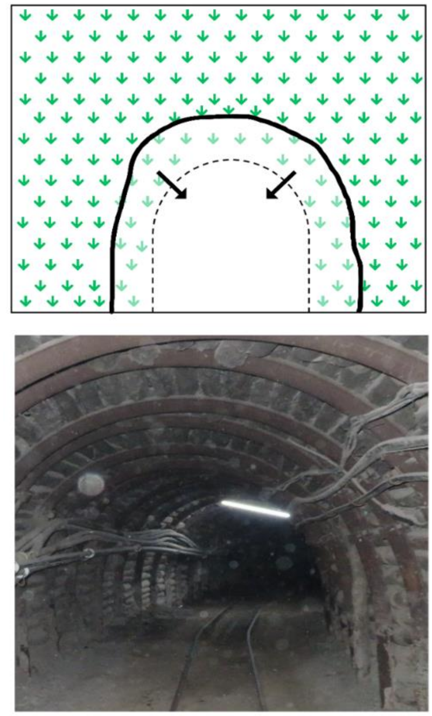

**Figure 5.** Relaxation zone in all directions within an underground excavation in massive serpentinite.

#### *3.2.2. Severe convergence*

In other sections of the underground excavation through the serpentinite rock mass at 510 m depth, frequent variations in behavior were recorded along the same excavation direction during advance. This horizontal variability in deformation is attributable to heterogeneous rock mass conditions. Field surveys and daily monitoring by mine controllers revealed that, over a 10 m span, moderate deformation of the steel sets (particularly along the sidewall) was followed by a zone of severe deformation and reduction of the excavation cross-section (Figure 7). These deformations manifested as cracking and even failure of the timber lagging, as well as significant distortion of already installed steel sets. This time-dependent phenomenon is associated with stress relaxation and represents a full shear failure process of the serpentinite rock mass.

## 4. Geomechanical properties of the serpentinite rock mass

Geomechanical properties of various types of serpentinite rock masses are used as input parameters in numerical modeling. These properties serve as essential parameters for the finite element-based numerical modeling software. The parameters for serpentinite Types 1, 2, and 3 were obtained from a previous study of Driouch et al. [1], while those for Type 4 were characterized in the laboratory through recent geotechnical testing.

The methodology adopted in the 2D numerical modeling is based on the widely used Hoek–Brown criterion, which provides an estimation of the strength and deformation properties of weak and heterogeneous rock masses [35], including both intact rock and heavily fractured rock masses. Hoek and Brown [33] originally proposed this empirical nonlinear failure criterion for fractured rock masses which estimates rock mass strength by integrating the contribution of both intact rock and discontinuities such as joints. The general form of this criterion, as defined by previous research [36] is expressed as follows:

$$\sigma_1' = \sigma_3' + \sigma_{ci}' \left( m_b \frac{\sigma_3'}{\sigma_{ci}'} + s \right)^a \quad (1)$$

where:

$\sigma'_1$: Maximum effective stress at failure.

$\sigma'_3$: Minimum effective stress at failure.

$\sigma'_{ci}$: Uniaxial compressive strength of intact rock.

$m_b$: Value of the Hoek–Brown constant *m* for the rock mass.

**s** and **a**: Dimensionless constants that depend on the condition and degree of fracturing of the rock mass (for intact rock, *s* = 1).

The constants mb, s, and a (reduced values for the rock mass material) can be calculated from the Geological Strength Index (GSI) using the following relations:

$$m_b = m_i \exp^{\left(\frac{GSI-100}{28-14D}\right)} \quad (2)$$

$$s = \exp^{\left(\frac{GSI-100}{9-3D}\right)} \quad (3)$$

$$a = \frac{1}{2} + \frac{1}{6}\left(e^{-\frac{GSI}{15}} - e^{-\frac{20}{3}}\right) \quad (4)$$

where:

mi: Hoek–Brown constant for intact rock.

GSI: Geological Strength Index.

D: Disturbance factor.

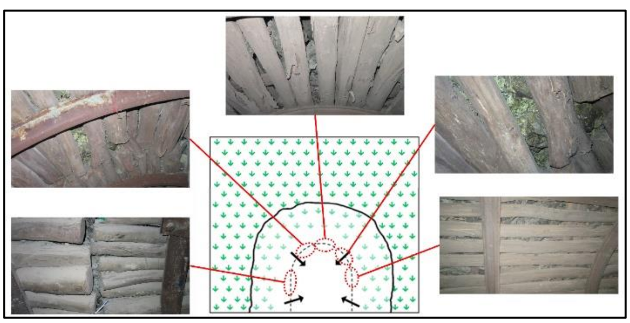

**Figure 6**: Centimetric deformation of the relaxation zone of massive serpentinite in an underground excavation.

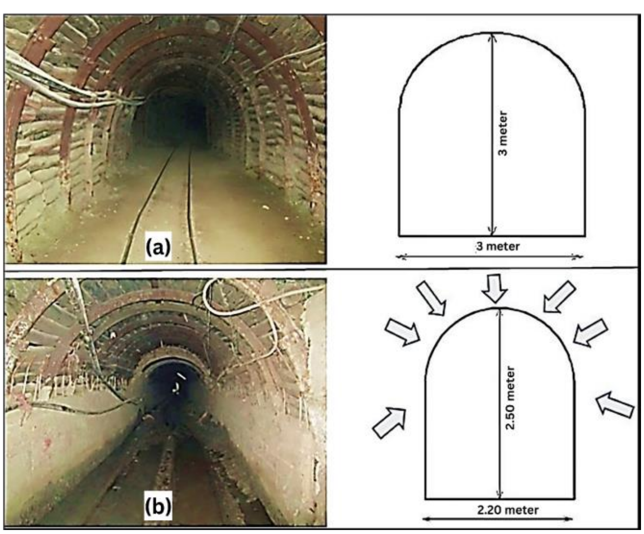


**Figure 7.** Illustration of the squeezing ground phenomenon observed during an underground excavation in serpentinite at a depth of 510 m. (a) Initial excavation with standard section; (b) Excavation with reduced section [1].

The use of the Hoek–Brown criterion makes it possible to estimate both the strength and deformability of a fractured rock mass, as well as the geomechanical input parameters required for numerical geotechnical modeling. This estimation is based on the uniaxial compressive strength of intact rock (σci), obtained through laboratory geotechnical testing, and on the Geological Strength Index (GSI), determined from a visual examination of serpentinite rock masses exposed on underground excavation faces, according to their petrographic nature and degree of fracturing. The range of GSI values used in this study, between 20 and 50, was determined from the reference chart of Marinos and Hoek [37] for the different serpentinite types at the Bou-Azzer mine [1]. This range indicates that the rock mass surfaces are highly fractured and partially disturbed, consisting of angular blocks with surfaces that are smooth, weathered, or moderately weathered.

The estimated results of the geomechanical parameters for the four serpentinite types at the Bou-Azzer mine, based on the application of the Hoek–Brown criterion, were obtained using the software RocData v.3.0 [38] and are presented in Table 1. A comparative graphical representation of the corresponding values of σci, GSI, and Em is provided in Figure 8.

The variation in uniaxial compressive strength for the serpentinite lithological unit shows scattered results, leading to four representative average values corresponding to the different facies observed in the Bou-Azzer East zone. Type 1 exhibits low geomechanical strength; Types 2 and 3 show moderate geomechanical strength, whereas Type 4 is characterized by very low geomechanical strength. This reflects the discontinuous nature of the rock mass and highlights the heterogeneity of this lithological unit, with variations from one zone to another due to fracturing and alteration of the rock mass. The results of the geomechanical parameters for the serpentinite rock mass indicate that the rock mass strength ranges from 0.241 to 4.282 MPa, while the deformation modulus ranges from 298.23 to 4348.71 MPa, revealing a significant variability in both strength and deformation properties of the rock masses at this mine, caused by intense deformation and hydrothermal alteration processes.

**Table 1.** Geomechanical parameters of the serpentinite rock mass [1].

| Parameters | Serpentinite Types | | | |
|---|---|---|---|---|
| | Type 1 | Type 2 | Type 3 | Type 4 |
| $\sigma_{ci}$ (MPa) | 18.60 | 29.10 | 33.61 | 5.00 |
| **GSI** | **40** | **45** | **50** | **20** |
| **Hoek–Brown Criterion** | | | | |
| **$m_b$** | 0.574 | 0.729 | 0.925 | 0.222 |
| **s** | 0.0003 | 0.0007 | 0.0013 | 2.33e-5 |
| **a** | 0.511 | 0.508 | 0.506 | 0.544 |
| **Mohr–Coulomb Criterion** | | | | |
| **C (MPa)** | 0.602 | 1.048 | 1.346 | 0.093 |
| **Ø (degrees °)** | 21.99 | 23.82 | 25.68 | 14.85 |
| **Rock Mass Parameters** | | | | |
| **$\sigma_{cm}$ (Mpa)** | 1.785 | 3.217 | 4.282 | 0.241 |
| **$E_m$ (Mpa)** | 1816.49 | 3028.73 | 4348.71 | 298.23 |

*mb: reduced value of the material constant; c: cohesion ; Ø: friction angle ; σcm: uniaxial compressive strength of the rock mass ; Em: deformation modulus of the rock mass.

## 5. Methodology of numerical modeling

In geotechnics, numerical modeling using the finite element method is a technique that treats the rock mass as a continuous medium. This modeling approach consists of developing a geometric excavation model that enables an elasto-plastic analysis, thereby allowing the study of stress distribution around the excavations and supplying information about the mechanical behavior of the rock mass for the geotechnical engineer. For this purpose, the 2D finite element software RS2 [39] was

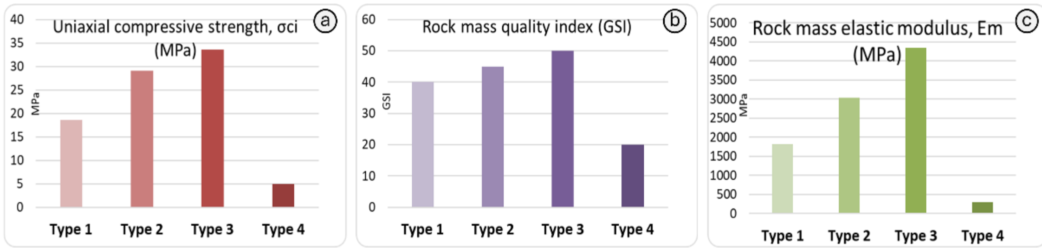


**Figure 8.** Representation of the uniaxial compressive strength σci (a), rock mass quality index (GSI) (b), and rock mass elastic modulus Em (c), for the four serpentinite types.

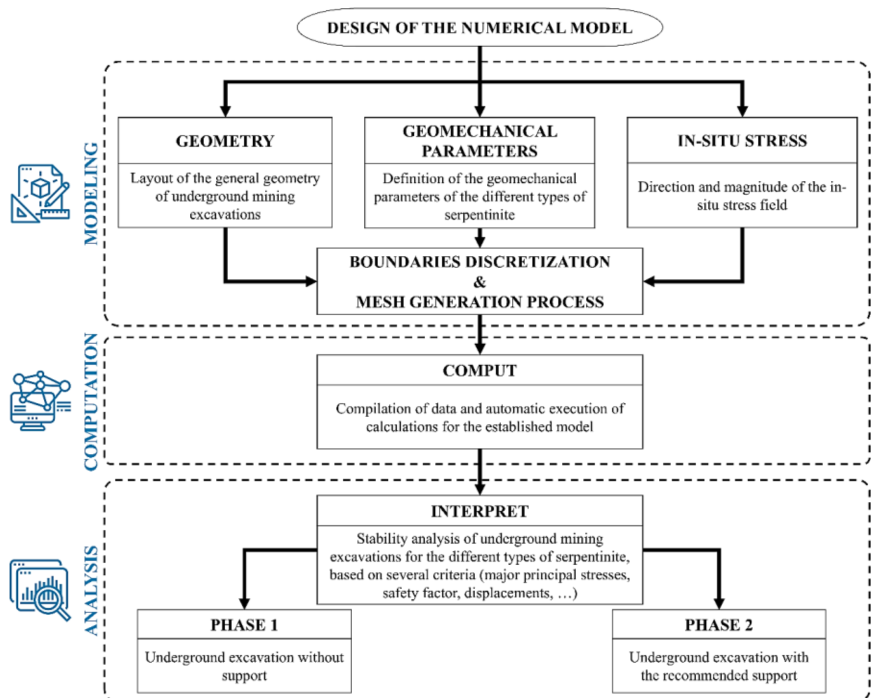


**Figure 9.** Flowchart of the numerical modeling of underground excavations in serpentinite of level 540 m showing the major steps of the simulation process.

selected, as it includes design modules that account for the properties of the rock materials and the stresses to which they are subjected, as well as the sizing of the support systems around the underground excavations.

The construction of the model begins with direct drafting, using the RS2 interface, of the geometry of an underground excavation at a depth of 540 m for the different types of serpentinite. The excavation dimensions are 2.5 m in span and 2.5 m in height. Boundary conditions adopted in RS2 consisted of restraining horizontal displacements along the lateral boundaries ($U_x = 0$) and restraining both horizontal and vertical displacements along the lower boundary ($U_x = U_y = 0$), while the upper boundary was left free. In-situ stresses were applied using the gravitational loading method.

The geomechanical parameters specific to each type of intact serpentinite rock are then introduced, such as uniaxial compressive strength, Young's modulus (E), Poisson's ratio (ν), and dry unit weight of the rock (γr), along with the parameters of the Hoek–Brown failure criterion (mb, s, and a). Direction and intensity of the in-situ stresses at the Bou-Azzer mine are also introduced, applied to the virgin serpentinite rock mass [1], as well as the boundary conditions. The orientation of the regional tectonic stress components at the Bou-Azzer mine ($\sigma_1$, $\sigma_2$, $\sigma_3$) was defined based on structural characterization studies, particularly those reported by Driouch et al. [40]. Stress magnitudes were estimated using empirical approaches developed for crystalline rock masses, in accordance with the work of Zang et al. [41].

RS2 software then generates a mesh from a predefined discretization. This step involves specifying the types of geometric elements used, namely triangular elements. In this study a six-node graded triangular mesh was adopted to ensure a fine and regular resolution of stress and displacement fields in the immediate vicinity of the excavation, while limiting the number of elements in more distant regions. The 2D numerical model was constructed under plane strain conditions. The mesh is then generated automatically. Finally, the calculation results are visualized according to several criteria (factor of safety, principal stresses, displacements), after data compilation and automatic execution of the calculations by the numerical modeling software.

It is worth mentioning that the factor of safety (FOS) was calculated using the shear strength reduction (SSR) method. In this approach, the shear strength parameters of the rock mass are progressively reduced until numerical instability or non-convergence is reached, and the corresponding reduction factor is taken as the factor of safety. The flowchart of Figure 9 illustrates the methodology used and the different steps of the simulation process.

## 6. Results of numerical modeling process

In this study, geotechnical numerical modeling of permanent excavations in serpentinites was carried out, considering two distinct scenarios: the excavation phase and the phase involving the implementation of the recommended support systems. The detailed results of this geotechnical numerical modeling are presented below for a depth of 540 m.

### 6.1. Excavation phase

At a depth of 540 m (Figure 10), the maximum displacement is very high during excavation in type 4 serpentinite, exceeding 41 cm. In contrast, the maximum displacements are moderate for type 2 and type 3 serpentinites, relative to the excavation dimensions. For type 1 serpentinite, the maximum displacement is also significant, exceeding 13 cm.

The factors of safety during the excavation phase are generally very low across all cases. For type 2 and type 3 serpentinites, values range between 0.40 and 0.76 at the crown, and between 0.53 and 0.74 at the sidewall. For type 1 serpentinite, the factors of safety range between 0.30 and 0.50 at the crown, and between 0.41 and 0.50 at the sidewall. In the case of type 4 serpentinite, the factors of safety are the lowest, ranging from 0.10 to 0.20 at the crown, and from 0.15 to 0.25 at the sidewall.

The stress distribution around the excavations in serpentinite at a depth of 540 m shows a marked increase in tangential stress at the crown, reaching a maximum of 42.8 MPa in all study cases. Conversely, the radial stress decreases sharply, with a very low maximum of only 1.8 MPa, due to the inward convergence of the crown toward the excavation. At the sidewall, the maximum tangential stress is 8 MPa, while the maximum radial stress is 0.8 MPa.

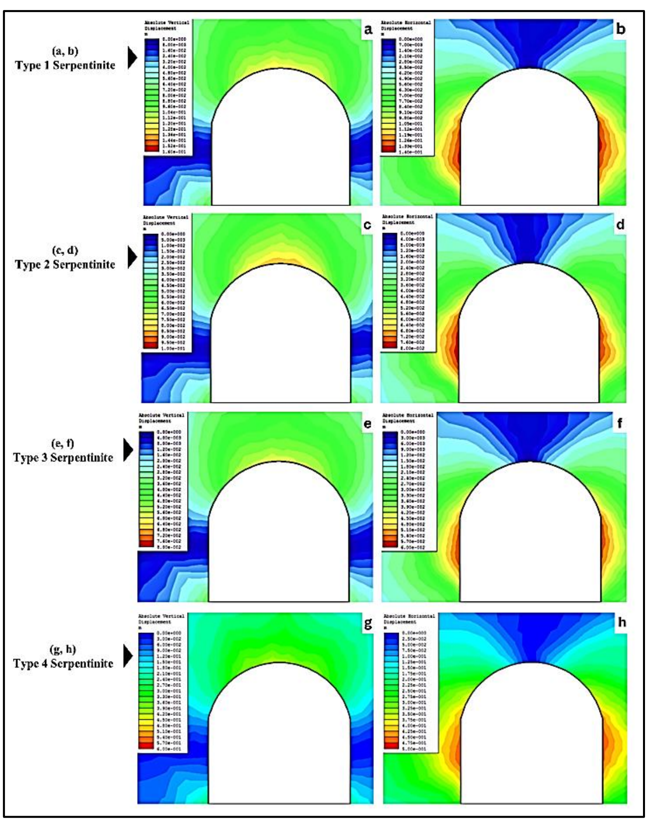


**Figure 10.** Displacement results of excavation simulation at a depth of 540 m. (a) Vertical displacement for type 1 serpentinite; (b) Horizontal displacement for type 1 serpentinite; (c) Vertical displacement for type 2 serpentinite; (d) Horizontal displacement for type 2 serpentinite; (e) Vertical displacement for type 3 serpentinite; (f) Horizontal displacement for type 3 serpentinite; (g) Vertical displacement for type 4 serpentinite; (h) Horizontal displacement for type 4 serpentinite.

### 6.2. After support installation

The recommended support systems for the excavations in serpentinite, at a depth of 540 m are presented in Table 2. These systems include steel arches, either light or heavy, with different spacings, complemented by a layer of shotcrete for excavations in type 1 and type 2 serpentinite, while a layer of reinforced concrete is recommended for type 4 serpentinite. The maximum displacement of the underground excavations for the different serpentinite types remains tolerable with respect to the span and height of the excavations after the installation of the recommended support.

**Table 2.** Recommended support systems for different excavations in serpentinites at a depth of 540 m.

| Serpentinite type | Required Support |
|---|---|
| Type 1 | • Sliding steel arches + lagging<br>• Spacing of 0.5 m<br>• Shotcrete (UCS = 30 MPa; t = 20 cm) |
| Type 2 | • Sliding steel arches + lagging<br>• Spacing of 0.5 m<br>• Shotcrete (UCS = 30 MPa; t = 10 cm) |
| Type 3 | • Sliding steel arches + lagging<br>• Spacing of 0.5 m |
| Type 4 | • Heavy steel arches (HEB-120 M) (52.1 kg/m), with spacing of 0.5 m<br>• Reinforced concrete (UCS = 45 MPa; t = 25 cm) |

*UCS: Uniaxial Compressive Strength.

*t: Shotcrete thickness.

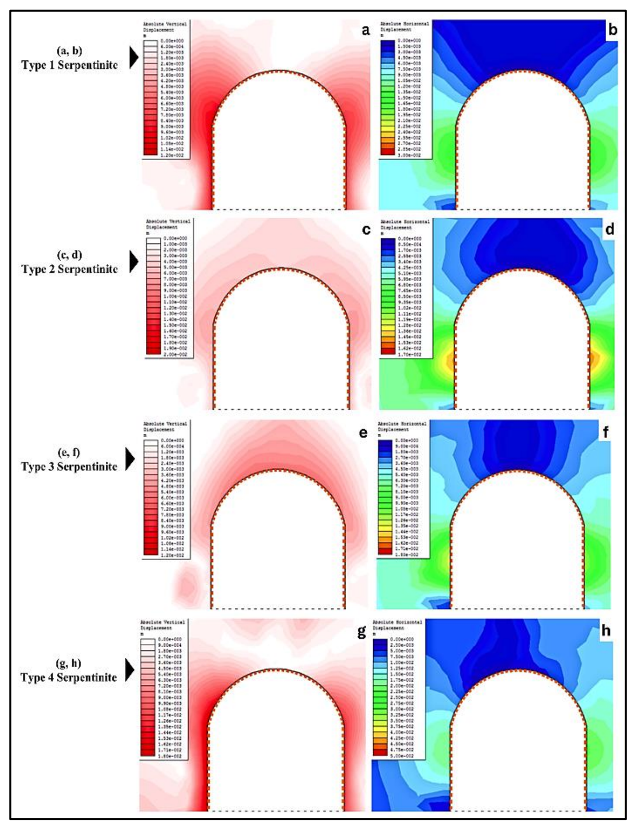


**Figure 11.** Displacement results of supported excavation at a depth of 540 m. (a) Vertical displacement for supported type 1 serpentinite; (b) Horizontal displacement for supported type 1 serpentinite; (c) Vertical displacement for supported type 2 serpentinite; (d) Horizontal displacement for supported type 2 serpentinite; (e) Vertical displacement for supported type 3 serpentinite; (f) Horizontal displacement for supported type 3 serpentinite; (g) Vertical displacement for supported type 4 serpentinite; (h) Horizontal displacement for supported type 4 serpentinite.

These maximum displacements range between 5 mm and 9 mm in the crown, and between 11 mm and 20 mm in the sidewall (Figure 11). The factor of safety in the serpentinite excavations after the implementation of the recommended support systems is improved in general. Specifically, the safety factors for type 1, type 2, and type 3 serpentinite range between 1.10 and 1.30 in the crown, and between 1.10 and 1.60 in the sidewall. For type 4 serpentinite, the safety factors range between 1.10 and 1.20.

## 7. Discussion

Geotechnical instability associated with squeezing ground conditions can create major technical and economic challenges as well as significant delays in excavation and support schedules. The instabilities observed in the Bou-Azzer East zone do not appear as block falls or structurally controlled block slides due to gravity, but rather as major rock mass collapses. This type of failure mechanism poses a serious challenge to both excavation and ground support. It is generally recognized that squeezing conditions lead to a reduction in the cross-section of an excavation, resulting from a combination of induced stresses and the relatively weak properties of the rock mass [5]. According to the International Society for Rock Mechanics (ISRM), squeezing behavior is essentially associated with time-dependent creep caused by exceeding the shear stress limit. This compression of the rock and the associated deformation that develops around the tunnel are also time-dependent, which means they may stop shortly after excavation or continue over a long period [42].

The geomechanical characterization of the serpentinite rock mass, carried out through laboratory testing, highlights significant variations in uniaxial compressive strength ($\sigma ci$) within this lithological unit. The measured values range from 5 MPa (minimum) to 33.61 MPa (maximum), depending on the different facies in the Bou-Azzer East region. Type 1 serpentinite exhibits low geomechanical strength, Types 2 and 3 show medium strength, while Type 4 is characterized by very low geomechanical strength. The poor geomechanical quality of the serpentinite rock mass is also reflected in the Geological Strength Index (GSI), evaluated using the base chart method proposed by Marinos and Hoek [37]. For the different serpentinite types at the Bou-Azzer mine, the GSI values range from 20 to 50.

Scientific studies addressing the design of ground support systems for underground excavations in squeezing ground conditions through numerical modeling remain scarce in the mining industry. According to a previous study, the numerical analysis of different support types for main tunnels intersecting a coal seam showed that the use of steel sets was highly effective in reducing wall displacements [43].

For underground excavations in serpentinite rock masses (whose geomechanical quality ranges from poor to very poor at the Bou-Azzer mine) the selection of suitable and reliable ground support systems represents a major challenge for geotechnical stability and the long-term durability of mining infrastructures. The design of such support systems relies mainly on empirical methods and past experience, both of which show clear limitations in this particular context, characterized by increased tectonic stresses and the squeezing ground behavior of the serpentinite, as confirmed by earlier studies by Driouch et al. [1].

The use of the most common empirical approaches in mining, such as the Rock Mass Rating (RMR) system by Bieniawski [7], the Tunnelling Quality Index (Q-system) by Barton [6], and the Rock Quality Designation (RQD) index by Deere [44], has clear shortcomings when applied to serpentinite rock masses of low geomechanical quality. The main limitations can be summarized as follows: the RQD does not adequately reflect rock mass quality, since it only considers the degree of fracturing while ignoring rock strength as well as the mechanical and geometrical properties of joints. Moreover, it does not provide a reliable measure of the actual degree of fracturing in the rock mass [45]. The RMR system, on the other hand, cannot be reliably applied to weak rock masses, since it is mainly based on case studies of competent rock [46]. Finally, the Q-system is also not suitable for weak, poor-quality rock masses. The support recommendations derived from these empirical methods (such as steel sets, rock bolts, and shotcrete) face serious implementation challenges and cannot guarantee the long-term stability of permanent underground excavations in serpentinite. The main limitation of these approaches lies in their qualitative characterization of the rock mass and their provision of only general, empirical guidelines, which are insufficient for detailed and reliable design. This makes them less relevant for serpentinite rock masses that are weak, heavily fractured, altered, and prone to squeezing ground behavior.

Field investigations conducted in the Bou-Azzer East region included in situ tests with systematic bolting using 1.8 m-long Split Set friction bolts. However, major issues arose during their installation: after drilling the boreholes in accordance with standard practices, they often became clogged or deformed, and once the bolts were installed, they would loosen or slip out of the serpentinite rock mass. Pull-out tests were attempted, but their execution proved problematic, as the bolts often detached during the setup of the testing device before the test could even begin (Figure 12). Other trials using Swellex friction bolts, cement-grouted bolts, and resin-grouted bolts produced the same outcome, with the bolts slipping out of the serpentinite rock mass.

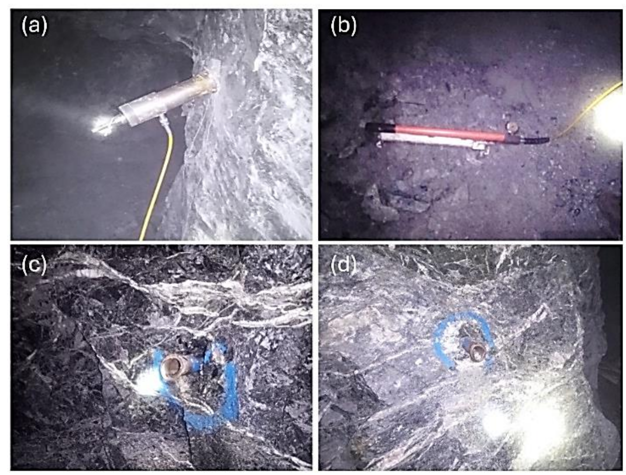


**Figure 12.** Pull-out test arrangement and observed borehole behavior. (a) and (b) Installation of the pull-out test device; (c) and (d) Deterioration of boreholes observed after drilling and bolt installation, highlighted in blue paint, as well as loosening around the test setup.

The results of maximum vertical (Uy) and horizontal (Ux) displacements at 540 m depth are represented in the two graphs of Figure 13, showing crown and sidewall behavior before and after support installation. These results show that the maximum displacement is extremely high in serpentinite type 4, exceeding 41 cm. This is explained by the fact that the vertical stress ($\sigma v$) is more than three times higher than the rock's uniaxial compressive strength. By contrast, maximum displacements range between 5 cm and 9 cm in serpentinite types 2 and 3. In serpentinite type 1, however, the maximum displacement also remains significant, exceeding 13 cm. The safety factors during the excavation phase are generally very low across all studied cases, ranging between 0.10 and 0.76 in the crown and between 0.15 and 0.74 in the sidewall.

Numerical simulation results based on the Hoek–Brown failure criterion highlight the decisive influence of depth, in situ stress state, and the geomechanical properties of the serpentinite rock mass on the deformation mechanisms and stability of underground mine excavations. An increase in depth leads to higher vertical and horizontal stresses, which in turn cause a redistribution of the stress field and a greater concentration of tangential stresses around the excavation boundaries. When these stresses exceed the strength of the serpentinite rock mass, a rapid transition to elasto-plastic behavior occurs, characterized by the onset of plasticity and the development of damaged or deformed zones surrounding the underground openings. Although the influence of the Hoek–Brown parameters was not specifically evaluated in this study, it is well established that the rock mass quality index (GSI) generally has a decisive effect on the extent of plastic zones and the magnitude of deformations. A decrease in GSI tends to enlarge the damaged zone, reflecting the strong dependence of mechanical behavior on the degree of fracturing.

The proposed support systems for serpentinite excavations at 540 m depth, derived from a combination of lessons-learned process, empirical methods, and field observations carried out in two main underground workings at 360 m and 510 m depth, include primarily surface support. These systems consist of sliding or heavy steel sets, combined with shotcrete and reinforced concrete in the case of excavations crossing serpentinite type 4. After the installation of these support systems, the maximum displacements observed in the different serpentinite types remain within acceptable limits relative to the span and height of the excavations. In addition, the safety factors of the excavations are significantly improved, ranging from 1.10 to 1.30 in the crown and from 1.10 to 1.60 in the sidewall.

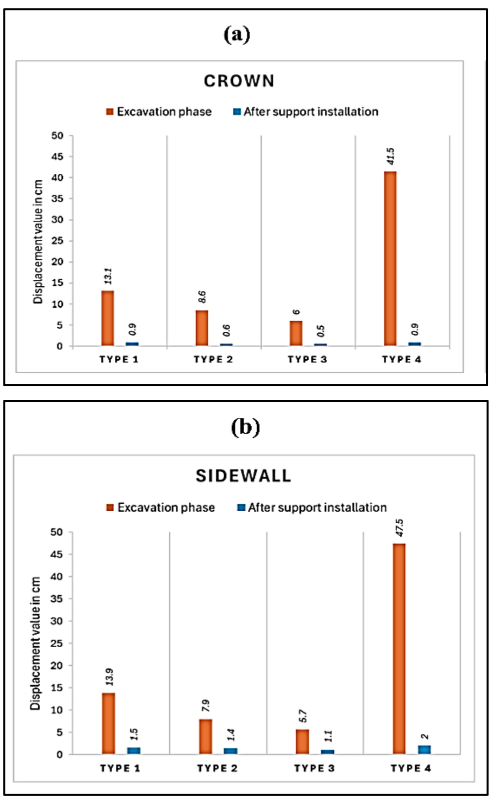


**Figure 13.** Graphical representation of the maximum vertical (Uy) and horizontal (Ux) displacement results for the excavations in serpentinite at a depth of 540 m. (a) Crown maximum displacement before and after support installation; (b) Sidewall maximum displacement before and after support installation.

## 8. Conclusions

The instability of mining excavations in the serpentinite rock mass at the Bou-Azzer mine represents a major challenge for the stability and long-term durability of strategic underground infrastructures. This instability is primarily linked to the exceedance of induced stresses relative to the compressive strength of the rock as mining projects advance to deeper levels beyond 500 m. As a result, significant reductions in the cross-sectional area of the excavations occur, along with failures of the installed support systems.

The objective of this study is to propose reliable and adapted support systems, using numerical modeling, for underground mining excavations depending on each type of serpentinite encountered at great depths, within the framework of the new Shaft 7 extension project in the Bou-Azzer East zone. The poor geomechanical quality of the serpentinite, combined with the increase in stresses with depth, is a key factor driving the squeezing ground behavior. This generates major techno-economic repercussions and significant delays in mining progress, making surface support systems, despite their relatively high cost, a current priority for this mine. Such support consists of lightweight sliding or heavy steel sets, complemented by shotcrete or reinforced concrete as an additional measure for excavations intersecting serpentinite of type 4. After the installation of these supports, the outputs of the numerical modeling showed satisfactory results in terms of deformation, since the maximum displacements observed in the different serpentinite types remained within tolerable limits relative to the span and height of the workings. The various numerical simulations confirm that this support method is effective in controlling the level of deformation. For future research, particular attention will need to be given to the use of geotechnical monitoring instruments such as extensometers and stress cells, as well as to the development of new excavation methods adapted to the specific conditions of the serpentinite rock mass. This would help enhance local and overall ground stability and ensure optimal conditions for mining operations in this mine. The present study is limited by the simplified representation of the complex mechanical behavior of serpentinite and by the use of a two-dimensional modeling framework. Future investigations should therefore rely on more advanced three-dimensional numerical tools, such as FLAC3D or 3DEC, to achieve a more realistic and sophisticated simulation of deep underground excavations.

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