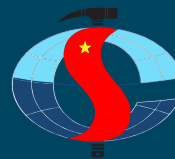




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Advances in the Earth, Mining and Environmental Sciences for Safe and Sustainable Development

Volume 2

Earth, Mine, and Environmental Sciences for
Green, Sustainable, and Prosperous Development
in the Era of a Nation's Rise



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AND ENVIRONMENTAL SCIENCES FOR SAFE
AND SUSTAINABLE DEVELOPMENT**

Volume 2:

**Earth, Mine, and Environmental Sciences for Green, Sustainable,
and Prosperous Development in the Era of a Nation's Rise**

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Foreword

The publication series “*Advances in the Earth, Mining and Environmental Sciences for Safe and Sustainable Development*” was conceived as a platform to promote scientific innovation, interdisciplinary collaboration, and knowledge exchange in support of safer, greener, and more sustainable development. *Volume 1: Advanced Technologies and Artificial Intelligence in the Earth and Environmental Sciences* established this foundation by highlighting the rapid emergence of digital technologies, artificial intelligence, and computational approaches that are reshaping the way we observe, analyze, and understand the Earth system.

Building upon this momentum, *Volume 2: Earth, Mine, and Environmental Sciences for Green, Sustainable, and Prosperous Development in the Era of a Nation’s Rise* extends the vision of the series into a broader scientific and societal context. While Volume 1 emphasized technological advancement, Volume 2 focuses on how these technologies - along with traditional and emerging scientific approaches - are being integrated to address real-world challenges related to environmental stewardship, sustainable resource management, climate resilience, and green growth.

This volume comprises 79 peer-reviewed articles contributed by authors from 10 countries and regions, reflecting an expanding network of international collaboration and the growing global commitment to advancing Earth, mining, and environmental sciences. The diversity of institutional backgrounds and research approaches represented here underscores the relevance of these topics to the shared pursuit of green, resilient, and inclusive development.

The volume is structured into three thematic parts, each representing a critical axis of sustainability-oriented research:

Part 1 – Earth, Mine and Environmental Sciences towards the Sustainability

This part brings together studies on geohazards, geotechnical engineering, mining science, hydrogeology, and environmental geology. The contributions highlight innovative approaches to landslide and geohazard assessment, advanced geotechnical modeling and underground construction behavior, sustainable mining practices, and environmental monitoring for land, water, and geological systems. These works reinforce the essential principles of ensuring safety, environmental protection, and sustainable resource utilization, forming the foundation for resilient national progress.

Part 2 – Digital Transformation for Prosperous Development

The second part illustrates how AI, machine learning, remote sensing, WebGIS, and geospatial intelligence are revolutionizing data acquisition, environmental monitoring, hazard prediction, and decision-making. The studies presented explore big data and deep learning techniques for landslide modeling, WebGIS-based early warning systems, UAV and hyperspectral imaging applications, groundwater forecasting, air quality assessment, and digital transformation-driven environmental governance. These contributions

demonstrate the transformative role of digital technologies in fostering prosperous, evidence-based, and future-ready development.

Part 3 – Green Development: Perspectives of the Earth, Mine and Environmental Sciences

The final part focuses on the scientific foundations and practical pathways toward green growth, environmental restoration, and sustainable livelihoods. The articles cover marine and coastal ecosystem management, microplastic pollution, wastewater treatment, green materials and circular economy solutions, biodiversity and climate-related studies, greenhouse gas monitoring, and sustainable tourism planning. Collectively, these contributions reflect a holistic, interdisciplinary approach to green development, integrating environmental science, socio-economic considerations, and policy-relevant insights.

As a whole, Volume 2 presents a comprehensive and timely collection of scientific advances that align with national and global priorities for sustainability. It showcases how Earth, mining, and environmental sciences are evolving to meet the challenges of a rapidly changing world, advancing the shared goal of a safer, greener, and more prosperous future.

We extend our sincere appreciation to all authors, reviewers, editors, and supporting institutions for their dedication and contributions. Their collective efforts have made this volume a meaningful addition to the scientific literature and a valuable reference for researchers, practitioners, policymakers, and students.

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Research of the relationship between rock mass elastic modulus and the maximum surface subsidence for developing a geomechanical model of the Khe Cham coal mine

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Abstract: The model allows the study of engineering problems in both heterogeneous and homogeneous environments, as well as in isotropic and anisotropic rock masses. The laws governing rock and soil displacement and deformation determine the distribution of stress, strain, the development of failure zones, and the height of the fractured zone. Their intensity depends on structural characteristics, the stratigraphic sequence of rock layers, and the cross-sectional geometry of mine workings.

This paper determines the elastic modulus of the rock mass using the RocData software. Based on this, the relationship between the elastic modulus and the maximum surface subsidence in the geomechanical model is established. A correlation function is constructed, and the coefficient $K_C = E_C/E_R = 1.24$ is determined for application to the Quang Ninh region.

Keywords: elastic modulus, subsidence, Khe Cham coal mine.

INTRODUCTION

For the calculation and construction of geomechanical models, and for the design of underground structures and underground mining operations, it is essential to obtain the mechanical-physical properties of the rock mass. In practice, there are many methods for determining these properties. Common approaches used in different regions include the Rock Mass Rating (RMR) classification, the Russian method that applies a structural

strength reduction coefficient for rock masses, and the empirical approach proposed by Hoek and Brown, which is based on the Hoek–Brown failure criterion for intact rock and rock mass, and considers the geological strength index (GSI) and the disturbance factor (D) due to blasting damage [Nguyen, T. S., & Pham, V. C. (2009); Nguyen, V. T. (2014)]

Currently, numerous empirical expressions are available to estimate mechanical parameters such as elastic modulus (Young's modulus), compressive strength, tensile strength, as well as internal friction angle and cohesion, in correlation with the indices RMR, GSI, and D.

The development of these methods reflects major scientific achievements in rock mechanics and geotechnical engineering worldwide, while also highlighting the complex mechanical behavior of rock masses governed by both geological conditions and mining technology.

Since these methods rely on different criteria, it is necessary to analyze and compare them to select the most appropriate (fit-for-purpose) approach and to further develop methods suited to Vietnamese conditions.

DETERMINING THE ROCK MASS ELASTIC MODULUS (E) FOR THE KHE CHAM COAL MINE

Overview of the geology in the study area

The Khe Cham coal mine is currently extracting longwall panels 13.1-8V and 12.7 in

the seams 12 and 13 using the full-caving longwall method, from level -225 m up to -100 m. The average depth from the ground surface to the active longwall faces is 220÷250 m. The geological conditions of the seams 12 and 13 are presented in Table 2.1, and a geological cross-section along line XII is shown in Figure 2.1 [Final Report of the Research Project].

Table 2.1. Geological conditions of the seams 12 and 13 [Khe Cham geological report.].

No.	Longwall parameter	Unit	Seam 12 & 13
1	Mining level	m	-225 ÷ -100
2	Seam thickness	m	1.9 ÷ 2.1
3	Seam dip angle	deg	10 ÷ 22
4	Overburden thickness	m	5
5	Longwall length along the dip direction	m	110 ÷ 105
6	Longwall length along the strike direction	m	90 ÷ 236
7	Average depth of the longwall	m	254 ÷ 222

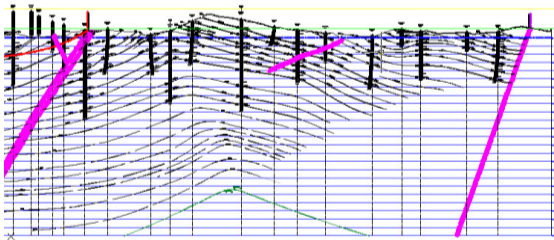


Figure 2.1. Geological cross-section along line XIIIB [Khe Cham geological report.]

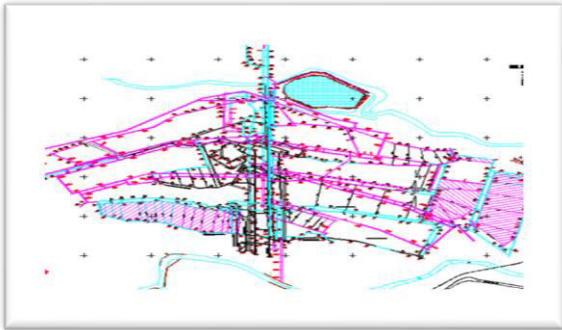


Figure 2.2. Layout of mine roadways (entries and drifts).

It is shown that the geological conditions for underground coal extraction at Khe Chàm are complex, notably due to folds and faults. These structures strongly affect deformation concentration zones and alter the geometry of subsidence troughs (displacement basins). Uniaxial compressive strength (UCS) test results for representative rock samples at Khe Cham are listed in Table 2.2 [Pham, D. H. (2011–2013)].

Table 2.2. Uniaxial compressive strength test results

No.	Rock type	UCS, σ (MPa)
1	Sandstone	114
2	Siltstone	42
3	Argillite	31
4	Coal	17.1

The elastic modulus (E) determined using Rocdata

To determine the elastic modulus E using RocData, it required inputs include uniaxial compressive strength (σ), Geological Strength Index (GSI), and the Disturbance factor (D) for the Quang Ninh coal basin. The GSI and D indices were selected following the expert judgment of Ngo Van Sy. The input data are shown in Table 2.3, and resulting elastic modulus is summarized in Table 2.4.

Table 2.3. Input data for Rocdata

No.	Rock type	σ (MPa)	GSI	Disturbance factor, (D)	Hoek–Brown constant, (m_i)
1	Sandstone	114	45	0.8	17
2	Siltstone	42	37	0.8	7
3	Argillite	31	11	0.8	4
4	Coal	17.1	8	0.8	4

Figures 2.3÷2.6 illustrate the Rocdata determination of E for sandstone, siltstone, argillite, and coal, respectively.

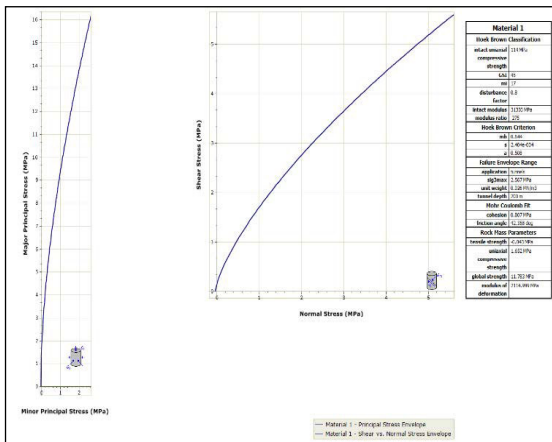


Figure 2.3. Determination of elastic modulus (E) for sandstone

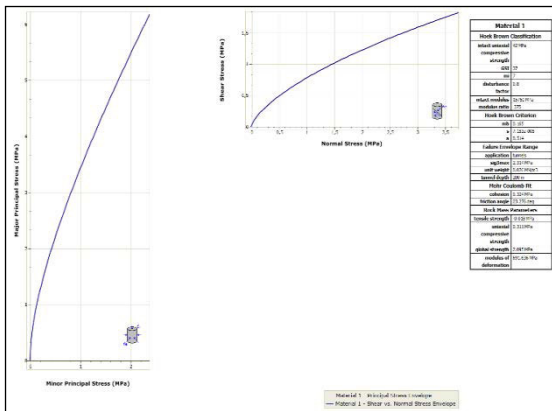


Figure 2.4. Determination of elastic modulus (E) for siltstone

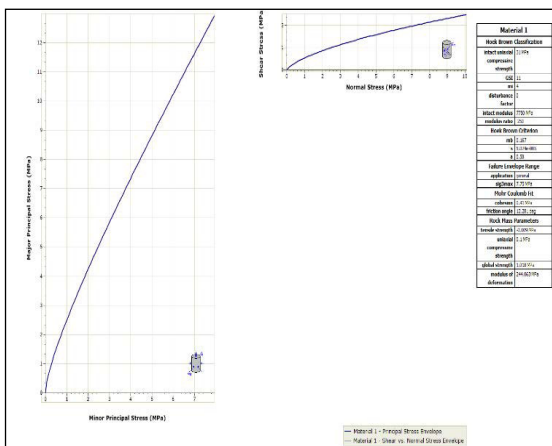


Figure 2.5. Determination of elastic modulus (E) for argillite

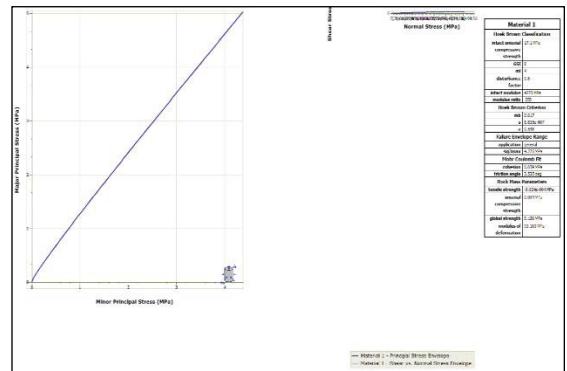


Figure 2.6. Determination of elastic modulus (E) for coal.

Table 2.4. Elastic modulus (E) determined by the Hoek-Brown criterion

No.	Rock type	σ (MPa)	GSI	Disturbance factor, (D)	Hoek-Brown constant, (m_i)	E (MPa)
1	Sandstone	114	45	0.8	17	2110
2	Siltstone	42	37	0.8	7	690
3	Argillite	31	11	0.8	4	242
4	Coal	17.1	8	0.8	4	93.01

ESTABLISHING THE RELATIONSHIP BETWEEN ELASTIC MODULUS AND MAXIMUM SUBSIDENCE

After determining the elastic modulus for each lithological layer in the Khe Cham coal mine, geomechanical models were constructed to calibrate boundary conditions against field behavior. Model outputs include maximum surface subsidence, horizontal strain, curvature, and tilt- which were then used to quantify the correlation between subsidence and elastic modulus E.

Geomechanical model development

To investigate the correlation between maximum subsidence and Young's modulus derived from Rocdata, six scenarios were analyzed using Rocscience 2.0. One scenario used the Rocdata values directly, while the other five varied the elastic modulus by 70%, 50%, 125%, 30%, and 10% of the baseline values, respectively. Poisson's ratio (ν) was kept constant in these scenarios.

- Case 1: E values from Rocdata—sandstone 2110 MPa, siltstone 690 MPa, argillite 242 MPa; constant ν .

- Case 2: E reduced to 70% of Rocdata—sandstone 1477 MPa, siltstone 483 MPa, argillite 169.4 MPa; constant ν .

- Case 3: E reduced to 50% of Rocdata—sandstone 1055 MPa, siltstone 345 MPa, argillite 121 MPa; constant ν .

- Case 4: E increased to 125% of Rocdata—sandstone 2637.5 MPa, siltstone 862.5 MPa, argillite 302.5 MPa; constant ν .

- Case 5: E reduced to 30% of Rocdata—sandstone 633 MPa, siltstone 207 MPa, argillite 72.6 MPa; constant ν .

- Case 6: E reduced to 10% of Rocdata—sandstone 211 MPa, siltstone 69 MPa, argillite 24.2 MPa; constant ν .

Results for the section oriented along the dip direction of the longwall

Figures 3.1÷3.6 show a clear trend: the larger the elastic modulus, the smaller the maximum subsidence, indicating a strong inverse correlation. The maximum subsidence (η) and the corresponding E values used in each case are summarized in Table 3.1.

Table 3.1. Maximum subsidence and elastic modulus

No	Rock type / Metric	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
1	Sandstone E (MPa)	2110	1477	1055	2637.5	633	211
2	Siltstone E (MPa)	690	483	345	862.5	207	69
3	Argillite E (MPa)	242	169.4	121	302.5	72.6	24.2
4	Coal E (MPa)	93.01	93.01	93.01	93.01	93.01	93.01
5	Maximum subsidence, η (m)	1.890	1.489	1.918	0.940	2.558	5.065

Figures 3.1÷3.6. Ground-surface subsidence profiles for Cases 1÷6.

For natural rocks, Poisson's ratio typically ranges from 0.1 to 0.3. In addition to the six scenarios above, two more models were run with $\nu = 0.1$ and $\nu = 0.3$, while keeping the elastic modulus values equal to those from

Rocdata. The results changes in maximum subsidence were insignificant compared to the base case with $\nu = 0.2$.

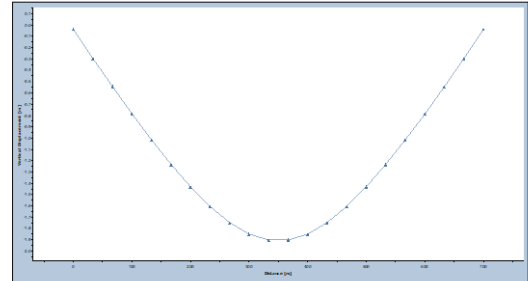


Figure 3.1. Ground surface subsidence in case 1

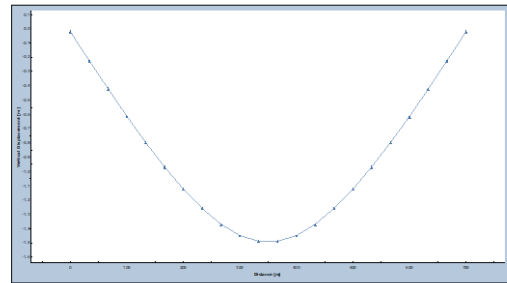


Figure 3.2. Ground surface subsidence in case 2

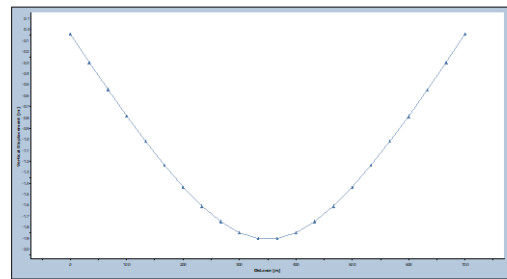


Figure 3.3. Ground surface subsidence in case 3

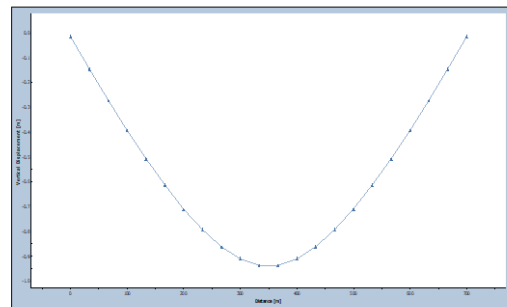


Figure 3.4. Ground surface subsidence in case 4

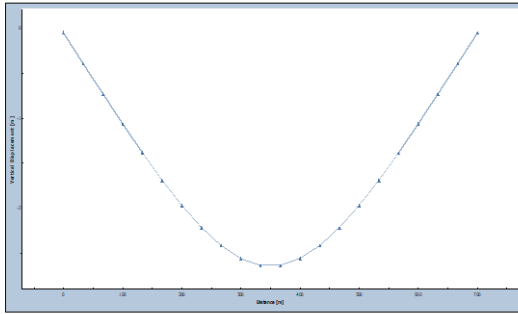


Figure 3.5. Ground surface subsidence in case 5

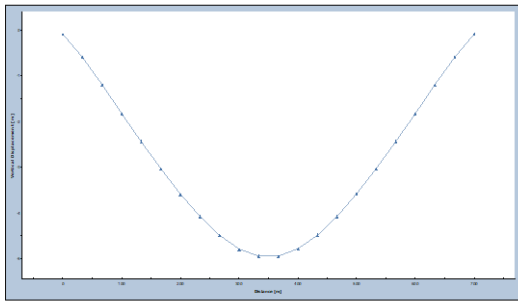


Figure 3.6. Ground surface subsidence in case 6

Relationship between the maximum subsidence and elastic modulus

Statistical analysis plays a key role in converting data obtained from experiments or natural observations into actionable knowledge. The statistical computing environment R (developed by Ross Ihaka and Robert Gentleman) was used to construct correlation plots and derive regression equations relating maximum subsidence (η) to elastic modulus (E) based on the data in Table 3.1 [Nguyen, V. T. (2014)].

To evaluate the significance of the interrelated influencing variables, statistical analysis and graphical language (using the R software) were applied to determine the correlation charts and the equations of the independent variables.

The database was obtained from Table 3.1, and the analysis results are as follows:

For sandstone, siltstone, and argillite, the correlation diagrams are shown in Figures 3.7÷3.9.

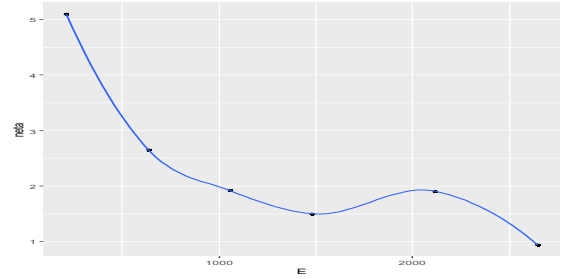


Figure 3.7. Correlation diagram between subsidence and elastic modulus of sandstone

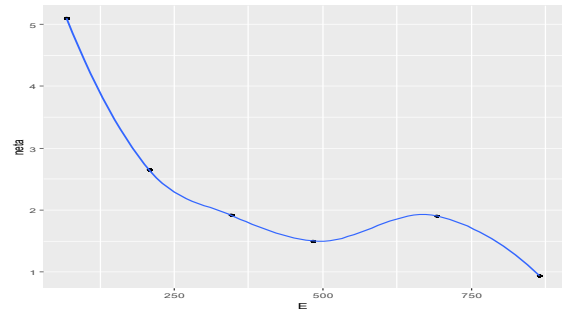


Figure 3.8. Correlation diagram between subsidence and elastic modulus of siltstone

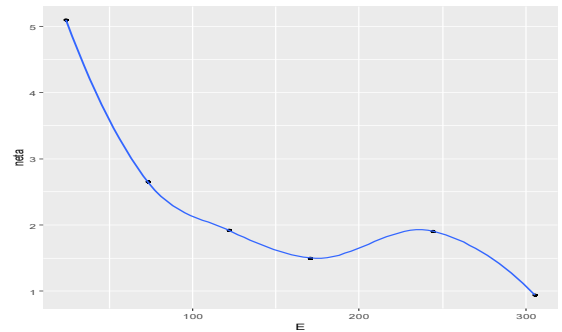


Figure 3.9. Correlation diagram between subsidence and elastic modulus of argillite.

The equation representing the correlation between the maximum subsidence and the elastic modulus of the rock types [Pham V. C. (2018)]:

$$\eta = a + EX + EX^2 + EX^3$$

For sandstone, with its elastic modulus, equation (3.1) is determined.

$$\eta = 7.01 - 1.04 \cdot 10^{-2} \cdot E + 6.50 \cdot 10^{-6} \cdot (E)^2 - 1.30 \cdot 10^{-9} \cdot (E)^3 \quad (3.1)$$

For siltstone, equation (3.2) is determined.

$$\begin{aligned} \eta = & 7.01 - 3.17 \cdot 10^{-2} \cdot E + 6.08 \cdot 10^{-5} \cdot (E)^2 \\ & - 3.72 \cdot 10^{-8} \cdot (E)^3 \end{aligned} \quad (3.2)$$

For argillite, equation (3.3) is determined.

$$\begin{aligned} \eta = & 7.01 - 8.99 \cdot 10^{-2} \cdot E + 4.88 \cdot 10^{-4} \cdot (E)^2 \\ & - 8.46 \cdot 10^{-7} \cdot (E)^3 \end{aligned} \quad (3.3)$$

Thus, by solving equations (3.1), (3.2), and (3.3), the elastic modulus E_C was determined, and the results are presented in Table 3.2.

Table 3.2. Results of calculating the elastic modulus of rock types [Pham V. C. (2018)].

No.	Parameter	Sandstone	Siltstone	Argillite
1	ER (MPa)	2115	691.36	244.03
2	EC (MPa)	2628.788	860.368	303.637

From the results presented in Table 3.2, it can be observed that if the elastic modulus calculated using the Rocdata software (E_R) is applied to the geomechanical model for any region, it becomes possible to predict surface displacement and deformation, as well as to determine the displacement parameters. This provides a basis for developing safe and effective mining solutions.

However, during data processing, when applying the geomechanical model to the Quang Ninh coal basin, the author identified a strength reduction coefficient determined according to equation (3.4) [Pham V. C. (2018)].

$$K_C = E_C / E_R = 1,2 \quad (3.4)$$

CONCLUSIONS

Around the world, numerous geomechanical models have been developed to analyze and predict ground surface movement and deformation, taking various forms. A comprehensive review and analysis indicate that these models all exhibit certain limitations and are generally of local applicability, being closely related to the specific geological conditions of each region or country. Geomechanical models that employ numerical methods possess a high degree of quantitiveness. The accuracy of such models depends on multiple factors, among which the

uniaxial compressive strength test is particularly important.

In practical studies on ground surface movement and deformation caused by underground mining, this dissertation employed a geomechanical model using input data from the Quang Ninh coal basin. The elastic modulus for the model was determined based on field-observed maximum subsidence values, which were used as boundary conditions to calibrate the geomechanical model for greater accuracy and realism.

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