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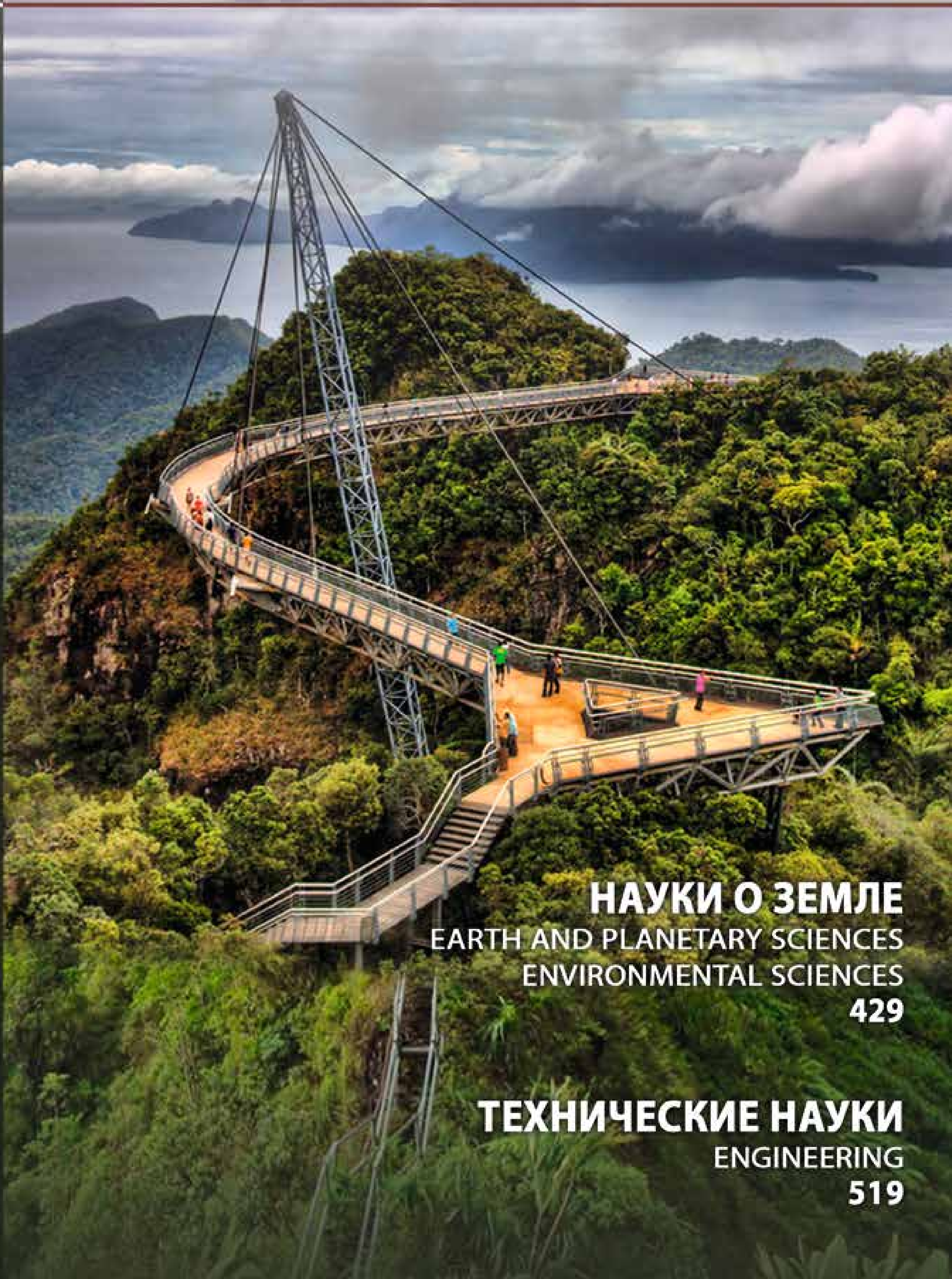

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СОДЕРЖАНИЕ

CONTENTS

STRATA MOVEMENT WHEN EXTRACTING THICK AND GENTLY INCLINED COAL SEAM FROM A PHYSICAL MODELLING ANALYSIS: A CASE STUDY OF KHE CHAM BASIN, VIETNAM

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Quang Ninh coalfield over the years has witnessed geotechnical issues such as surface subsidence and strata caving, deformation and fracture due to the underground coal mining. These issues have been preliminarily investigated mostly by using field observation.
The corresponding solutions and measures, however, seem to be inactive and perfunctory. This paper presents an analysis of height of strata caving, evolvement of deformation and movement zone, caving angle in strike direction, surface subsidence and strata movement when mining thick-gently inclined and/or closely distributed coal seams by using a physical model based on a case study of Khe Cham basin, Quang Ninh coalfield, Vietnam. The model shows that roof strata cave cyclically with a height being 5-6 times mining height; caving angle ranges from 64 to 67 degrees; maximum subsidence magnitude stabilises around 1.5 m; and strata behaviour caused by the mining of lower seam is less severe as that of the upper seam. The paper's findings are useful for engineers to better plan and design technical solutions to improving safety in thick coal seam extraction.

КЛЮЧЕВЫЕ СЛОВА:
Physical Modelling, Subsidence, Movement, Deformation, Caving, Khe Cham.

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1. Introduction

Mining operation by underground method creates voids below surface and changes pre-mining stress state. The rocks surrounding an underground excavation tend to move to reach a new equilibrium state of stress. Different points in surrounding rocks and on surface at a certain time move in different magnitudes, resulting in vertical deformation (title, curve, twist) and horizontal deformation (compressive, tensile, slip). Movement and deformation of rock strata caused by underground mining can form zones of subsidence, caving, deformation, fracture and toppling on surface. This consequently interrupts normal operation of equipment such as hoist, lift and plants; increases slope failure, gas emission and water inrush into mining area; and changing surface and underground water conditions [1 – 4].

Mining practice from Quang Ninh coalfield in Vietnam over the years reports a number of broken/damaged facilities caused by underground mining such as: sinking and inclination of fan station at level +142 Mao Khe coal mine; water burst from open pit into Adit +60 Thong Nhat coal mine; water burst from watercourse and used roadways into mining areas at Vang Danh and Mong Duong coal mines with flow rate up to 200 m^3/h. These incidents, however, were only preliminarily investigated by using field observation. Corresponding solutions and measures seem to be inactive and perfunctory. An improved understanding of strata movement and deformation caused by Quang Ninh underground mining is therefore of particular importance and necessity to the efficiency and productivity of Vietnam coal industry.

This paper presents an analysis of height of strata caving, evolvement of deformation and movement zone, caving angle in strike direction, maximum surface subsidence and strata movement when mining thick-gently inclined and/or closely distributed coal seams by using a physical model based on a case study of Khe Cham basin. The paper's findings are useful for engineers to better plan and design technical solutions to improving safety in thick coal seam extraction.

2. Development of physical model

2.1 Study site

The site of study includes thick and gently inclined coal seams at Khe Cham basin, which are representative for Quang Ninh geo-mining conditions. According to [5], coal reserves distributed in these seams is approximately 150,446 tonnes, accounting for 47.4% of total coal reserves at Khe Cham basin. The geological setting along the cross-section XVI of the basin is used for the study with following information. The strata include interbedded conglomerate, sandstone, siltstone, claystone and two main coal seams. Seam 10 is 55 m underneath surface and is 8 m thick; immediate roof is siltstone with an average thickness of 5 m while main roof is sandstone with a thickness of 30 m. Seam 9 is 65 m below Seam 10 and is 5 m thick; immediate roof and floor are mainly siltstone with thickness of 11 and 9 m, respectively while main roof is 20 m thick of sandstone. The inter-burden between two seams is clay-coal with an average thickness of 2.5 m. The rock properties of Khe Cham coal basin are shown in Table 1 [5].

2.2 Model frame

In accordance with strata movement analysis when mining thick-gently inclined

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Table 1

Rock properties at Khe Cham coal basin

Rock unit	Compressive strength, kg/cm²	Yield strength, kg/cm²	Volume weight, g/cm³	Specific weight, g/cm³	Internal friction angle, degree	Cohesion strength, kg/cm²
Conglomerate and sandstone	1785-178 966.88	258-208 233	2.79-2.4 2.56	2.87-2.56 2.67	32°	381.66
Sandstone	1778-111.8 966.88	223-1.16 97.31	2.85-2.51 2.64	2.93-2.69 2.72	31°	324.88
Siltstone	1086-114 48	171-36 87.5	2.84-2.5 2.65	2.92-2.1 2.73	30.34°	213.55
Claystone	204-124 168.41		2.65-2.43 233	2.59-2.52 2.56		

coal seam, a physical model is designed in a flat frame with rotational axis being perpendicular to the frame plane, which is based on the prototype of VNIMI [6]. The dimension of model frame is 3590 mm in length, 2244 mm in height and 1648 mm in thickness. Rotational angle of the model is from 0 to ±90 degrees, as illustrated in Fig.1.

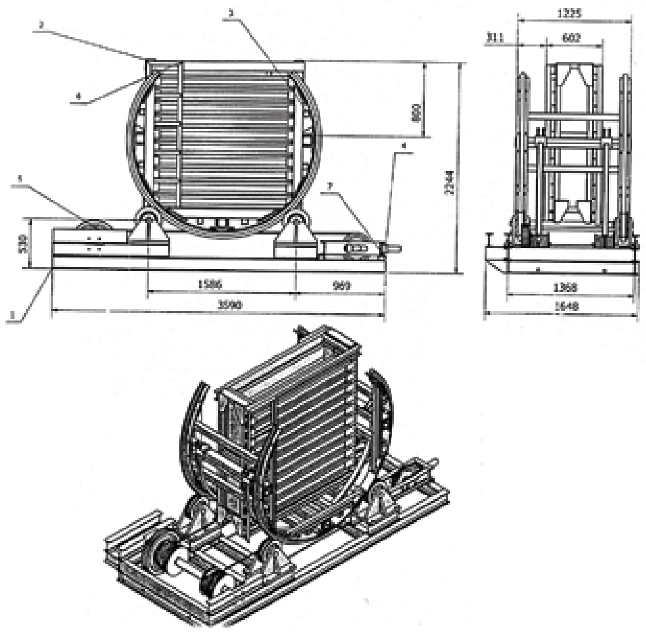

Fig. 1. *Model frame with 1– base frame, 2– rotational frame, 3 – drum frame, 4 – pull leg, 5 – drive part, 6 – ladder part, 7 – cable part*

2.3 Uniformity ratio and equivalent material in model

The model is 200 mm in length, 1500 mm in height and 1500 mm in thickness with a uniformity ratio regarding length of 1:100. Uniformity ratio regarding volume weight is 0.6:1 (0.6 gram in model is equivalent to 1 tonne in reality) while the ratio regarding time is 1:10. The material properties in model are calculated according to uniformity ratios and shown in Table 2.

Materials for building model are mainly composed of quartz sand, mica, talc powder, paraffin, chalk and clay. To ensure the equivalent material has properties conforming to the above uniformity ratios, it is necessary to carry out processing and combining these components together. The coordination rate follows the composition diagrams in Fig. 2 [7]. This work is carried out and tested many times (at least 03 experiments per sample) in the laboratory with specialized equipment. The test results are presented in Table 3.

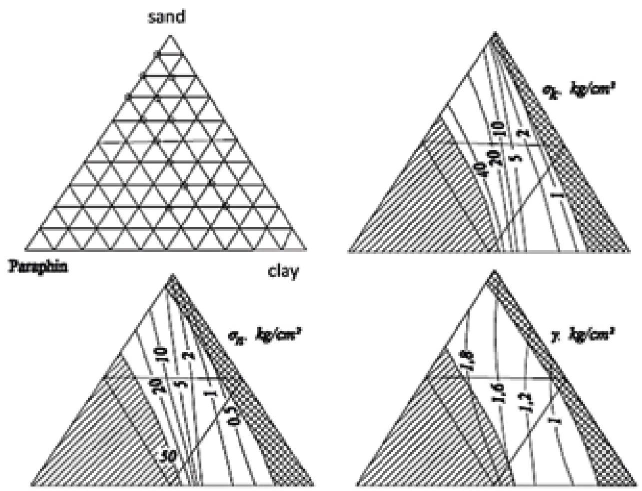

Fig. 2. *Composition diagram of paraffin-sand-chalk mixture*

2.4 Model construction

The model is constructed in upward sequence. Layers are equally horizontally laminated with a thickness of 1 cm per layer. To avoid the inter-cohesion between layers, an interval of 15 minutes is used for each layer building while a density of 0.046 g/cm² of mica is placed between two layers. The process for setting and building model is as follows [5]:

Step 1: selection of material component, calculation of material uniformity ratio to real rock strata;

Step 2: calculation of volume of all model materials;

Step 3: blending materials in 5 to 10 minutes then drying at 1250⁰C in 30 minutes. After each 10 minutes

Table 2

Uniformity ratio of rock material parameter in physical model

Parameter	Symbol, equation	Value
Length	α_l	1:100
Volume weight	α_γ	0,6:1
Time	α_t	1:10
Weight	$\alpha_m = \alpha_\gamma \times \alpha_l^3$	$0,6:10^6$
Tensile, compressive strength	$\alpha_{nén} = \alpha_{kéo} = \alpha_l \cdot \alpha_\gamma$	0,6:100
Cohesion strength	$\alpha_C = \alpha_l \cdot \alpha_\gamma$	0,6:100
Internal friction angle	$\alpha_\varphi = tg\varphi_{TT}/tg\varphi_M$	1:1
Young modulus E	$\alpha_E = \alpha_l \cdot \alpha_\gamma$	0,6:100
Poisson *v*	$\upsilon_{TT}=\upsilon_{M}$	1:1

Table 3

Result of testing sample for model

Component	Properties		Mixture				Properties	Temperature
	Density, g/cm^3	Weight, g	% according to weight	% according to volume	Grain size	Porosity		
- Quart sand - Clay - Paraffin	2,5 2,74 0,9	225 4,11 54	32,5 59,5 8,0	30 50 20	0,15 0,40	36,0 48,0	σ_n = 2,1 kg/cm^2 σ_k = 0,5 kg/cm^2 = 1,62 g/cm^3 σ_n/σ_k = 4,0	130

the mixture is blended to ensure the paraffin is equally melted into quart sand and clay;

Step 4: when the mixture's colour turns into dark yellow, put it into tank then stirring at 1300^{0}C in 45 minutes;

Step 5: clean and install model frame;

Step 6: place materials into model frame.

The result of model construction is shown in Fig. 3

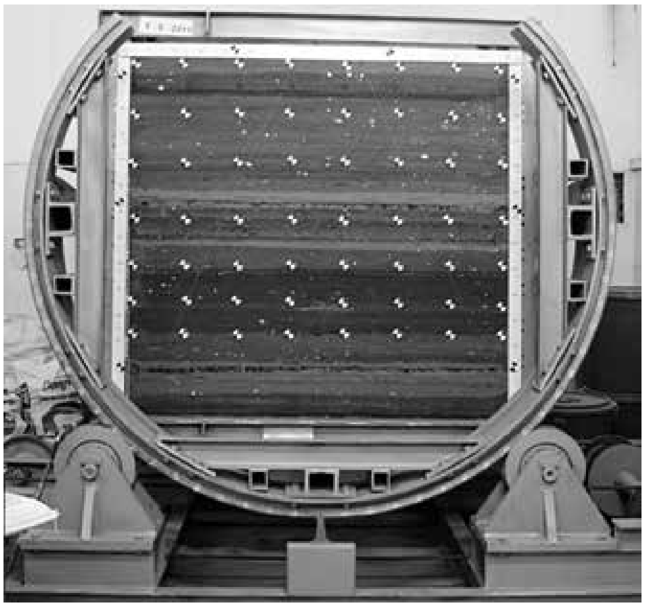

Fig. 3. *Physical model after construction*

2.5 Modelling of extraction

The model simulates a retreat longwall mining with top coal caving. To model the progressive mining, wooden prop is removed sequentially in accordance with real face advance. That is, one wooden prop is removed after every 2.4 hours, which is equivalent to a face advance rate of 1 m per day. Top coal recovery is manually implemented by using rake with a recovery rate of 70 %, equivalent to 4.5 cm thickness in Seam 10 and 2 cm thickness in Seam 9.

Seam 10 is extracted first then mining Seam 9. Before mining the lower seam, an interval is allowed for complete movement of rock strata caused by the upper seam extraction. To minimise the impact of truncated boundary condition, 20 cm length of material at left and right boundaries are unmined.

2.6 Model monitoring

To monitor the strata movement, a monitoring network is installed by placing markers (points) in the model. Markers that aligned on one horizontal line form one observation line. There are 12 lines from I to XII downward. Each line consists of eight points from 1 to 8 from left to right.

The observation is implemented by using photometric method with camera Nikon D7000 in combination with image data processing software Microstation, IRAS/C. The model is photographed at an interval of 15 minutes [8]. The photographing continues until the complete displacement of rock strata. The error in observation is calculated by testing model in several times [8].

3. Movement and deformation laws of rock strata and surface

3.1 Height of strata caving

The model extraction shows that the underground mining causes strata movement and deformation and consequently forms zones of subsidence, fracture and caving. The caving zone is dependent on the dimension and length of face advance. The near-field caving zone forms together with caving spans with a height of 10-12 cm in the model, which is equivalent to 10-12 m in reality (Fig. 4).

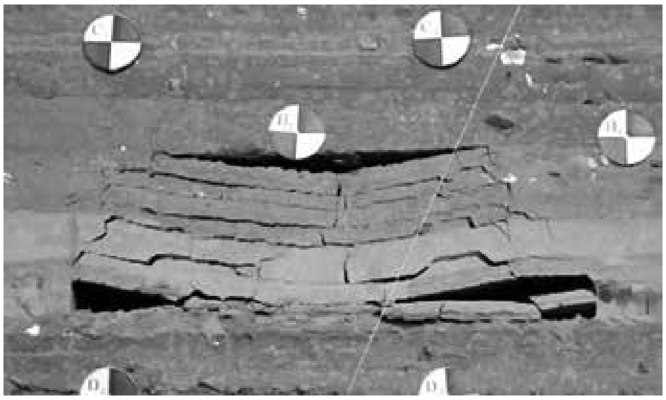

Fig. 4. Extraction and caving of roof strata in model

During the mining, immediate roof caves to form a complete caving zone while main roof sags afterward in larger span and forms fractured zone [9]. The model shows that the height of complete caving zone increases as the face advances. At 80 m of face advance, the caved rock fills the void caused by mining. The caving height remains stable around 10–12 m, which is 5–6 times the mining height, as plotted in Fig. 5.

3.2 Evolvement of displacement and movement area

The roof strata above caving zone are severely deformed and form fractured zone in shear and tensile fracturing. The fracture system is clearly observed at and around mining area while it is less observed at further area [10]. It is seen from the model that the roof strata move in block shape whose dimension is in linkage with caving span. When coal face advances far enough, a new caving span occurs, and the roof strata behave as cantilever beams. This rock movement repeats as the face advances, creating new fractures around coal face while closing far-face fractures. As a result, it is concluded that the movement and deformation of roof strata is in discrete and wave-cycle form.

3.3 Caving angle in strike direction

Caving angle in strike direction is defined as the angle between tangential line of caving zone and horizontal line. Observation from model indicates that the caving angle fluctuates between 64 and 67 degrees (Fig. 6). This angle is consistent with the angle theoretically calculated according to VNIMI's method, which is 65 degrees [6].

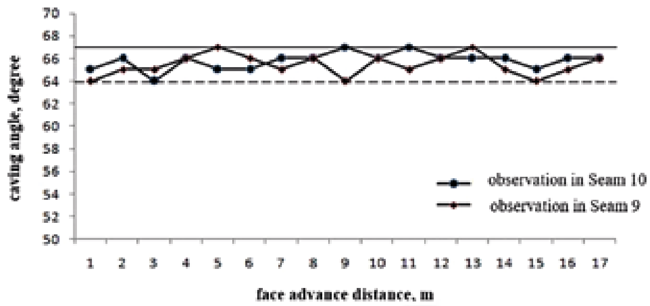

Fig. 6. Caving angle in strike direction when face advances

3.4 Surface subsidence

The model shows that the distance of face advance affects surface subsidence. When the face advances to a certain distance, the subsidence magnitude is stable around its maximum value and is independent of face distance [11; 12]. It is seen that by photometric method, no surface subsidence is observed within 20 m of face advance. When face advances at 30 m, the surface subsides and reaches 0.4 m at 40 m of face advance. The subsidence rapidly increases from 0.4 to 1.4 m when face advances from 40 to 65 m, then stabilising at 1.5 m. The bottom of subsidence curve shifts from concave shape to flat shape. This demonstrates that when the face advances far enough, one cycle of roof strata movement is complete (Fig. 7). The maximum subsidence in the model is close to the value theoretically calculated according to VNIMI's method, which is 1.6 m [6].

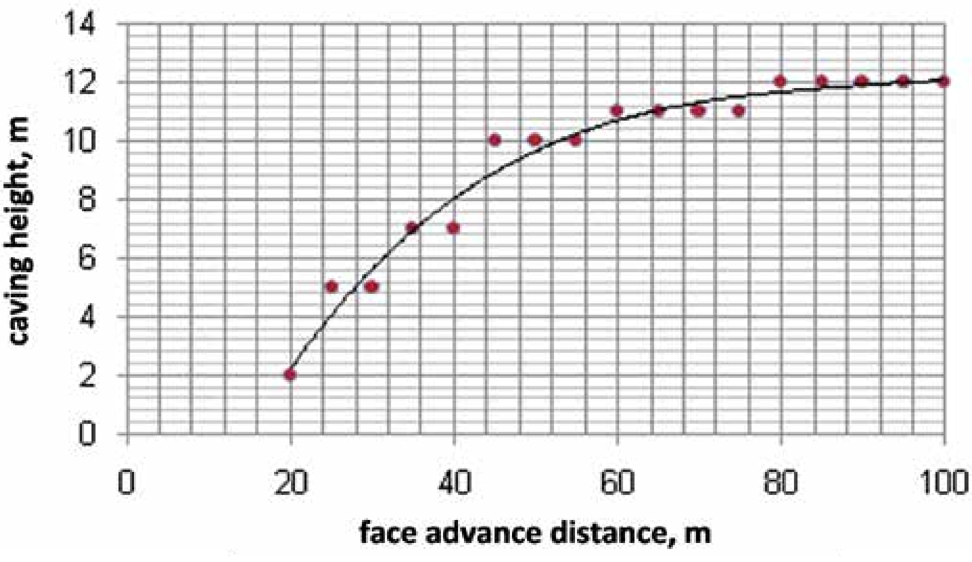

Fig. 5. Relationship between caving height and face advance distance

The model observation shows that at a certain depth of cover, a small distance in face advance does not significantly affect the surface.

When the distance increases, the zone of deformation and movement increases toward surface, forming subsidence basin. The subsidence at centre of the basin reaches a maximum value of approximately 70-80% of mining height before stopping increasing. This is because caved rock fills up mining void and prevents roof strata to move downward (Fig. 8).

3.5 Strata movement when mining closely distributed seams

In initial operation, the mining at Seam 9 does not significantly affect the mining at Seam 10 and surface. However, when the face advances far enough, the deformation and movement zone above Seam 9 increases to Seam 10. Roof strata above these seams are significantly deformed. The monitoring reveals that although this process is essentially not different from first extraction (at Seam 10), there is no tension, delamination and large tensile fracture as in mining Seam 10. This is due to the fact that the roof strata above Seam 10 have been broken and reduced their stability.

The surface subsidence caused by mining both Seam 9 and 10 increases and is proportional to the face advance distance. The maximum value reaches the total thickness of both seams, which is 2.9 cm in the model (Fig. 8).

Results from the physical modelling enable to establish deformation and movement laws of roof strata and surface, as illustrated in Fig. 9.

4. Conclusions

Based on a case study of Khe Cham basin in Quang Ninh coalfield of Vietnam, the authors have investigated roof strata movement and surface subsidence caused by longwall mining by developing a physical model. The conclusions are as follows:

- The underground mining creates a zone of complete caving. The zone's dimension is dependent on the distance of face advance, reaching a maximum value when the face advances about 80 m. Roof strata cave cyclically with a caving height being 5-6 times the mining height;
- Caving angle of roof strata in strike direction fluctuates between 64 and 67 degrees;
- Surface subsidence increases significantly at the face distance of 40 to 65 m, corresponding to a magnitude of 0.4 to 1.4 m, respectively. The maximum subsidence value is 1.5 m. The bottom of subsidence basin shifts from concave shape to flat shape;
- Rock strata behaviours such as tension, delamination and large tensile fracture when mining the lower seam (Seam 9) are not as severe as those when mining the upper seam (Seam 10) due to the previous rock failure and movement.

The paper's findings are helpful to engineers for designing driving/extraction schedule and pillars for efficiently and safely mining thick-gently inclined coal seams.

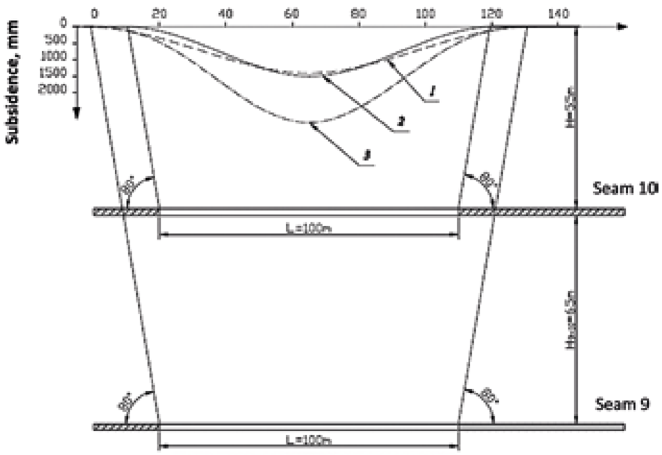

Fig. 8. *Caving angle and subsidence caused by extractions of single seam and all seams*

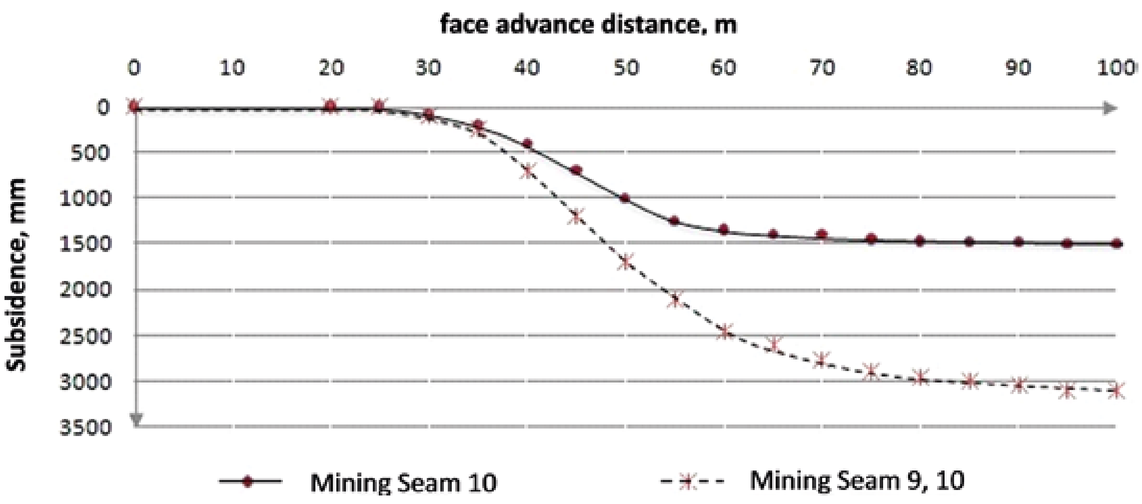

Fig. *7. Relationship between face advance and surface subsidence*

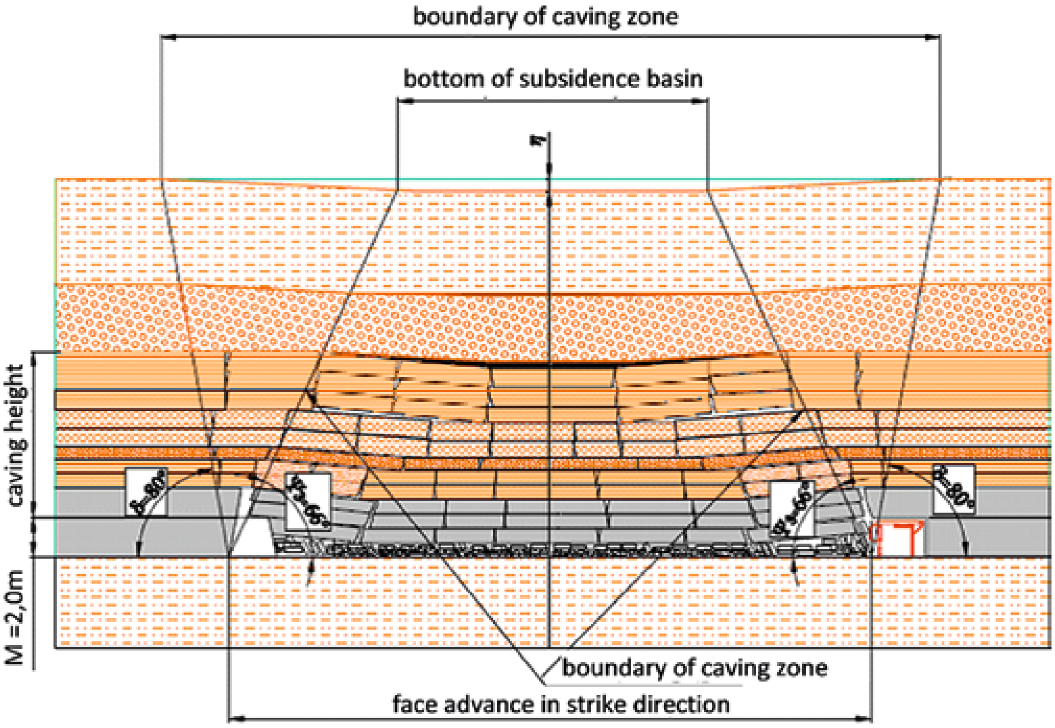

Fig. 9. *Deformation and movement of roof strata and surface in physical model (Ψ_3 – caving angle in strike direction; δ – angle of movement; η – maximum subsidence)*

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ДВИЖЕНИЕ ПЛАСТОВ ПРИ ИЗВЛЕЧЕНИИ ПЛОТНОГО И ПОЛОГОГО УГОЛЬНОГО ПЛАСТА ИЗ АНАЛИЗА ФИЗИЧЕСКОГО МОДЕЛИРОВАНИЯ: НА ПРИМЕРЕ БАССЕЙНА КХЕ-ЧАМ, ВЬЕТНАМ

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Куангнинское угольное месторождение на протяжении многих лет было свидетелем геотехнических проблем, таких, как оседание поверхности и обрушение пластов, деформация и разрушение из-за подземной добычи угля. Эти вопросы были предварительно исследованы в основном с помощью полевых наблюдений. Однако соответствующие решения и меры представляются неактивными и поверхностными. В настоящей работе представлен анализ высоты обрушения пластов, развития зоны деформации и движения, угла обрушения в направлении удара, оседания поверхности и движения пластов при разработке мощных пологих и/или близко расположенных угольных пластов с использованием физической модели, основанной на примере бассейна Кхе-Чам, угольного месторождения Куангнин, Вьетнам. Модель показывает, что кровельные пласты прогибаются циклически с высотой в 5-6 раз больше высоты горной выработки; угол обрушения колеблется от 64 до 67 градусов; максимальная величина просадки стабилизируется около 1,5 м; и поведение пластов, вызванное разработкой нижнего пласта, менее серьезно, чем поведение верхнего пласта. Выводы статьи полезны инженерам для лучшего планирования и разработки технических решений по повышению безопасности при добыче мощных угольных пластов.

Ключевые слова: физическое моделирование; просадка; движение; деформация; обрушение; Кхе Чам.