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RESEARCH NOTE

Physical Model Test and Numerical Simulation Study of Deformation Mechanism of Wall Rock on Open Pit to Underground Mining

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ABSTRACT

Based on the engineering background of Daye Iron Mine in Central China`s Hubei Province, the deformation mechanism and influence area of wall rock in the process of open pit to underground mining with high-steep slope was studied using physical model test and numerical simulation. Firstly, the selected typical section of the research was generalized, the physical model built with similar materials, special methods used to simulate the mining practice, dial indicators and digital camera measurement used to monitor the model deformation during the whole mining process. Secondly, the numerical model was built and the mining practice simulated using numerical simulation software to verify the results of physical model tests. The results indicate that the final failure of wall rocks appear at the areas nearing the ore body and does not have great influence on the stability of underground slope, the wall rock displacements of model increase slowly with increasing the mining depth. The displacements change laws of rocks nearing the faults are the same as other rocks at the same depth; the results of physical model test are generally in agreement with the numerical simulation.

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NOMENCLATURE

E	Modulus of elasticity（Mpa）	σ_t	Tensile strength（Mpa）
C	Cohesion（Mpa）	σ_c	Compressive strength（Mpa）
Greek Symbols		φ	Internal friction angle（^{o}）
γ	Specific weight（KN/m^3）		

1. INTRODUCTION

With the continuous mining of open-pit mines in China, the open-air mineral resources are declining rapidly, so more and more mines will turn to underground mining and most of them will prefer non-pillar sublevel caving methods to underground mining [1, 2]. In the process of open pit to underground mining, high-steep slope and underground mining operation influence and restrict each other. The existence of high-steep slope affects the safety and grade dilution of sublevel underground mining, and sublevel underground mining in turn affects the stability of the slope [3-6]. Therefore, it is necessary to study and master the interaction mechanism between high-steep slope and sublevel underground mining in order to guide safe and efficient underground mining.

Field experiments, model tests and numerical simulation are research methods currently used in the studies of geotechnical engineering [7-10]. The inadequacies of field experiments are long period, high cost and difficulties in stress monitoring [11-14]. Because of the complexity of influence factors in underground mining, the results of numerical simulations depend to a large extent on appropriate selection parameters [15, 16]. Physical model tests can overcome the inadequacies of field experiments and

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numerical simulations, the monitoring data are convenient for qualitative and quantitative analysis [17-19]. YIN Guang-zhi et al. studied the ground pressure of surrounding rock of large angle working coalface after mining in Xiangshan coal mine through photo-elastic experiments and field measurements [20]. Olivier Deck et al. enabled a parametric study of the soil–structure interaction and tested an analytical model of loading assessment to study the structures subsidence affected by underground mining [21]. LI Xiao-shuang et al. studied the stresses and deformation law of open-pit mines slope and surrounding rock during the process of underground mining in east section of Jinning Phosphorite mine through model tests [22]. LI Bing et al. studied the block ores generation of non-pillar sublevel caving in Chengchao iron mine through indoor model tests [23]. Marwan Al Heib et al. presented a new large small-scale physical model ($6m^3$) for studying the damage to structures and soil–structure interaction effect of large vertical displacement owing to underground mines [24].

These research results have important guiding significance on field engineering, however, these tests singly focused on stabilities and deformation law of slope in open-pit mining or stability and deformation law of surrounding rock and ground surface in underground mining, the experimental researches of interaction mechanism between high-steep slope and sublevel underground mining are rare. In view of this, this paper studied the influence mechanism between high-steep slope and non-pillar sublevel caving method during the processes of open-pit to underground mining based on the mining act of Daye iron mine by using physical model tests.

2. PHYSICAL MODEL TEST

2. 1. Project Overview Daye iron's east open-pit is made up of three ore blocks, which named Elephant Trunk Hill, Lion Hill and Jianshan from east to west (Figure 1), after decades of open-pit mining, the area forms large-scale ultra-high steep open-pit slope up to 230~430m, with tilt angle from 38° to 43°. The model test research is about ultra-high steep slope and caving method model test underground mining of Daye iron whose typical research section located in Lion Hill block. The upper part of the section is diorite while the lower part is marble, which is 200 meters from east to west, 800 meters from north to south, and 500 meters in depths; the underground non-pillar caving method mining depth is -168m.

2. 2. Model Generalizing Figure 2 shows the typical section of Area A in Lion Hill, the rock of this section can be generalized into diorite, marble, magnetite and backfilling body. The geologic structure of this section can be generalized into two developmental faults F9 and F25. The range of the section is 800m(length) ×200m (width) ×500m(height).

2. 3. Similar Principles The analysis of similar principles in the tests is the key to guarantee physical phenomena to be similar to the prototype.

Figure 1. Aerial view of Daye iron mine

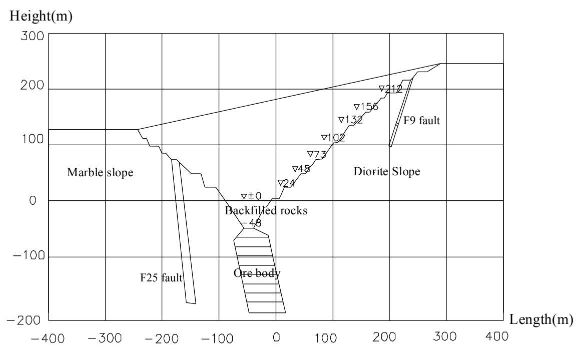

Figure 2. Geological section

TABLE 1. Main physical and mechanical parameters of similar materials

Rock type		γ	E	σ_c	C	φ
Marble	Prototype	27	1.62×10^4	48.54	0.26	30
	Model	27	54	0.16	$8.67e^{-4}$	30
Diorite	Prototype	27	1.8×10^4	98.18	0.27	29
	Model	27	60	0.33	$9e^{-4}$	29
Magnetite	Prototype	41.2	1.4×10^4	69.99	0.35	42
	Model	41.2	46.7	0.23	$1.16\ e^{-3}$	42
F9 fault	Prototype	—	—	—	0.03	18
	Model	—	—	—	$1e^{-4}$	18
F25 fault	Prototype	—	—	—	0.13	23
	Model	—	—	—	$4.3e^{-4}$	23

According to elastic-plastic mechanics equation or dimensional analysis method, the balance of model, geometry, physics and boundary condition equations, the geometric similarity constant is 300, main physical and mechanical parameters of similar materials are shown in Table 1.

2. 4. Similar materials A new kind of similar material of underground caving mining model test which consists of iron ore powder, barite powder, quartz sand, unsaturated resin, gypsum is developed through 1000 times material mechanics tests in nearly 10 months, iron ore powder. Barite powder and quartz sand are main materials, and the unsaturated resin and gypsum are cementing agent (Table 2). A new kind of simulated fault which consists of polypropylene films and soft clay is also developed, polypropylene films are fault planes, soft clay are fault fillings [25, 26]. Similar material and the simulated fault have obtained Chinese invention patent authorization (No. 201210189082.X).

2. 5. Model monitoring system The whole physical model was built with similar material bricks as the geological section（Figure 3）. In order to facilitate observation, the marble and dioritic parts were painted blue and white, respectively. Considering the laboratory conditions and the maneuverability of existing monitoring methods, two kinds of methods are adopted to monitor the whole process of the model tests, dial indicators were adopted to monitor the deformation of slope, and digital camera measurement for monitoring the deformation of the whole model. The arrangement of monitoring points is shown in Figure 3.

2. 6. Mining Simulation With a full consideration of the technologic features in open-pit mining and non-pillar sublevel caving, the process of open-pit into underground mining by super high steep slope can be divided into 3 stages. Stage 1, open-pit mining proceeded through man-powered drilling up blocks, where it extends middle part to both sides and the depth untill it forms a V-shape and reaches the depth of minus 48 meters. Stage 2, backfilled the mining pit to the depth of 0 meters with waste rocks, monitoring the wall rock deformation and keep the slopes stable. Stage 3, underground mining proceeded blasting the blocks along the ore boundary from the east to the west, whose sublevel height is 4 cm, sublevel drive interval is 3.3cm and ore caving interval is 2.5cm (Figure 4).

When the mining of each segment completes, the fragments from drilling up can be spontaneously filled into the goaf. Then, mine the next ore body after the deformation stability. Take photos of each step before and after the mining, read the centesimal meter and real-time monitor the data.

TABLE 2. Mixture ratio of similar materials (%)

Raw material	Marble	Diorite	Magnetite
Iron ore powder	22.8	27.2	19.4
Barite powder	37.1	39.3	55.9
Quartz sand	13.2	8.9	7.6
Unsaturated resin	4.3	3.9	3.5
Gypsum	12.3	10.5	4.3
Pure water	6.5	6.7	6.1
Glycerol	3.8	3.5	3.2

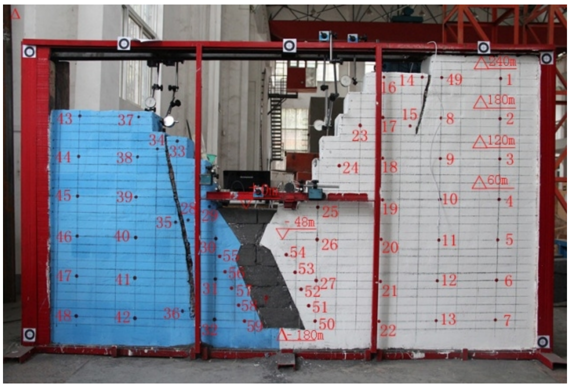

Figure 3. Arrangement of monitoring points

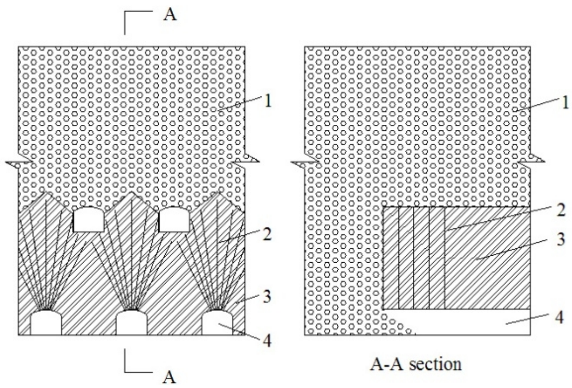

Figure 4. Process flowsheet of non-pillar sublevel mining

3. DISPLACEMENT OF SLOPE

The mining step-slope displacement curves of each typical monitoring points are drawn and shown as in Figure 5 (from south to north is the positive direction of horizontal displacement, upward is the positive direction of vertical displacement). Figure 5 shows that springback occurs at the toe of south and dioritic slope during the process of open-pit mining. The biggest springback occurrs at No. 25 point of dioritic slope toe and its value is 0.057mm. After that, the springback reduces to 0.018mm because of the waste rock backfilling. It shows that waste rock backfilling can stabilize the slope toe and ensure the slope stability before the underground mining.

Horizontal displacement of all the measuring points increases during the step 3 mining. During the underground mining process of step 4-12 from -72m to-168m, horizontal displacement of dioritic slope increases more rapidly than marble slope since the extrusion of dioritic slope is more obvious than marble slope. After the step 13 mining, the vertical displacement of point 16 at toe of dioritic slope is the biggest and the value is -0.15mm, while the horizontal displacement of point 25 at toe of dioritic slope is the biggest and the value is -0.23mm. With the increase of mining depth, the vertical displacement and horizontal displacement of both slopes increase almost linearly. The total displacements of the marble slope are always smaller than the dioritic slope in the whole mining processes.

4. Displacement of wall rock

The mining step-displacement curves of each typical monitoring point are drawn and shown as Figure 6 (from south to north is the positive direction of horizontal displacement, upward is the positive direction of vertical displacement). Figure 6a shows that the vertical displacements of the shallow monitoring points increase more rapidly than the deep points with the increase of open-pit to underground mining depth, and underground mining has a greater influence on the shallow stope wall rocks than deep rocks.

Figure 6b shows that the horizontal displacements of the monitoring points increase slowly with the increase of mining depth; the effects of open-pit mining for horizontal displacements of wall rock are not obvious. The wall rock disturbance of underground mining and the emergence of east-west free face instantaneously make the horizontal displacements increase rapidly. For example, point 54 is in the level of -60m, the horizontal displacement of point 54 increases slowly before mining to -60m depth When mining from -60m to -72m depth, the horizontal displacement is increasing rapidly, then the horizontal displacement increases slowly again after mining to -72m depth.

5. DISPLACEMENT VECTOR

The distribution of displacement vectors of the model are shown in Figure 7 which show that:①The displacement vector of wall rocks, marble and dioritic slope increase with the mining depth increasing, the displacement vector directions are downward the goaf. ②The change trend of the rocks nearing the faults is not obvious. ③The main deformation of the model are mainly vertical displacement, horizontal displacement change is relatively small and only the horizontal displacement of the slope toe is relatively large.

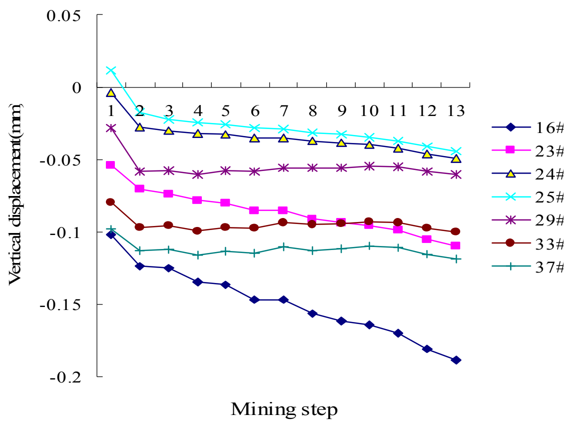

Figure 5a. Vertical displacement curves of slope points with mining steps

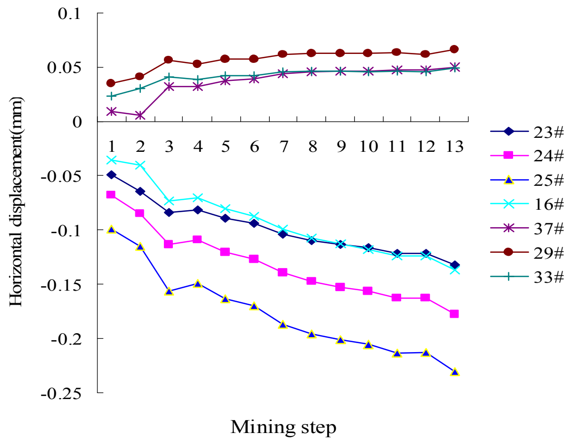

Figure 5b. Horizontal displacement curves of slope points with mining steps

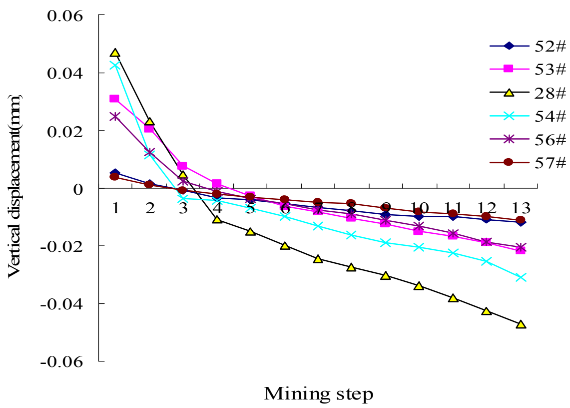

Figure 6a. Vertical displacement curves of wall rock points with mining steps

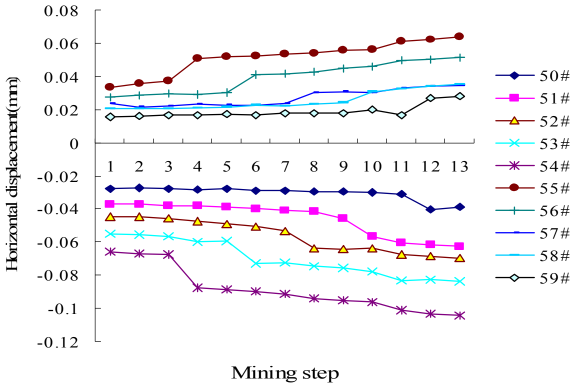

Figure 6 b. Horizontal displacement curves of wall rock points with mining steps

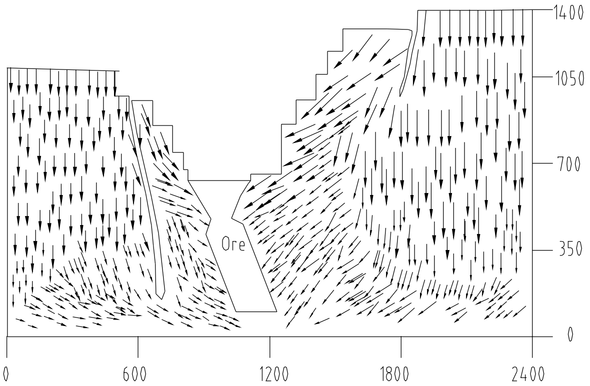

Figure 7. Distribution of displacement vector (unit: mm)

TABLE 3. Main mechanical parameters of wall rock

Rock type	γ	E	σ_c	σ_t	C	φ
Marble	27	1.62×10^4	48.54	5.79	0.26	30
Diorite	27	1.8×10^4	98.18	6.37	0.27	29
Magnetite	41.2	1.4×10^4	69.99	5.15	0.35	42
F9 fault	—	—	—	—	0.03	18
F25 fault	—	—	—	—	0.13	23

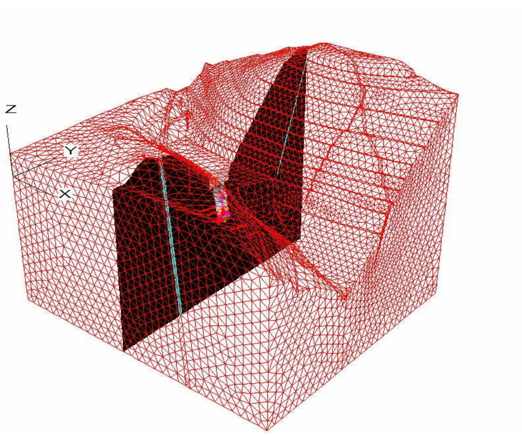

Figure 8. 3D numerical model and typical section

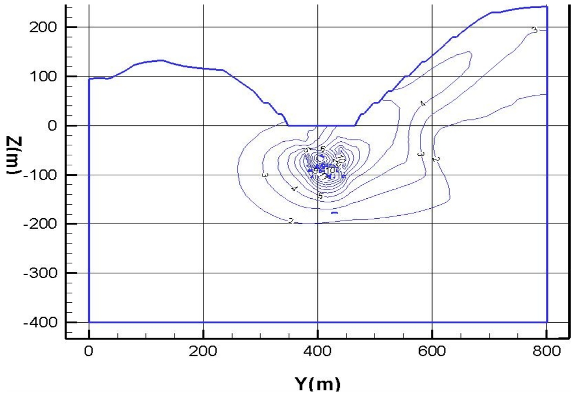

Figure 9. Rock displacement contour after open-pit mining

6. VERIFICATION OF NUMERICAL SIMULATION

In order to verify the results of physical model test, FLAC3D software waas used to analyze the comparison between numerical simulation and physical model test. Three-dimensional finite element model of Daye Iron Mine is established and the typical cross section of physical model test was chose as the research object, the engineering geological conditions is the same with model test and the mechanical parameters of wall rock are shown in Table 3. The 3D numerical model and typical section of numerical simulation are shown in Figure 8. The whole mining process is divided into 13 steps. The 1st step is sublevel caving along the ore boundary to -48m The 2nd step is backfilling waste rocks to ±0m.The 3rd -13th steps are underground mining along the ore boundary and backfilling. Parts of the displacement contour of wall rock are shown in Figures 9, 10 and 11, the results of numerical simulation show that:

1. The impact on rock deformation gradually increased with the process of open-pit to underground mining, the vertical displacement and horizontal displacement of both slopes increase with the increase of mining depth.

2. The displacements change law of rocks nearing the faults are the same with other rocks at the same depth. The rock deformation of dioritic slope are bigger than marble slope.

3. The maximum settlement and maximum horizontal displacement are 50.9 mm and 62.7 mm while the results of model test are 47.3mm and 68.1mm, respectively. The rock displacements change laws in the numerical simulation are almost the same with model test. Both the numerical simulation and physical model test can reveal the same mutual influence mechanism between ultra high-steep slope and underground mining; the results of physical model test are generally in agreement with the numerical simulation.

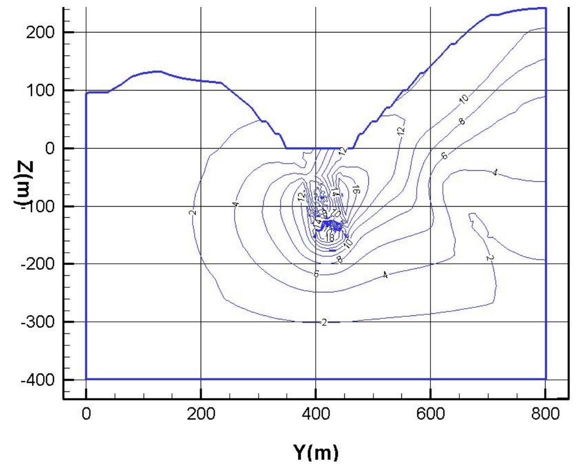

Figure 10. Rock displacement contour after mining to -120m

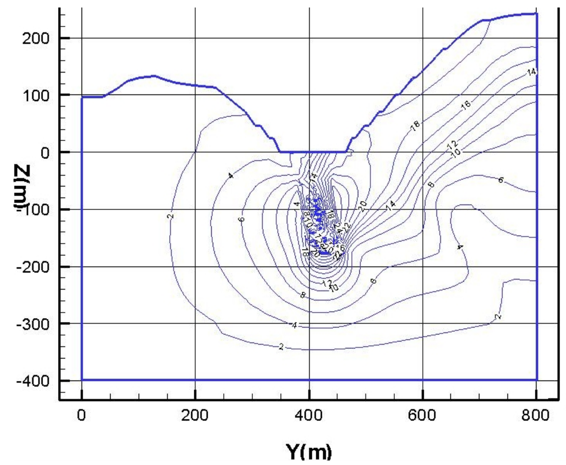

Figure 11. Rock displacement contour after mining to -180m

7. CONCLUDING REMARKS

The physical model tests and numerical simulation not only simulate the complex geological conditions of selected sections, but also reasonably simulate the mining processes of open-pit mining and sublevel caving without sill pillar.

With the increase of mining depth, the vertical displacement and horizontal displacement of both slopes increase almost linearly. The total displacements of marble slope are always smaller than dioritic slope in the whole mining processes. The effects of underground mining for slope are not obvious except for the toe of dioritic and marble slope. Open-pit to underground mining does not have great influence on the stability of underground stope in Daye iron mine.

Mutual authentication between numerical simulation and physical model can make a genuine and believable research conclusion So it is reasonable to use both methods to study the mutual influence mechanism between ultra high-steep slope and underground mining.

8. ACKNOWLEDGEMENTS

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چکیده

بر اساس زمینه مهندسی معدن آهن Daye در استان هوبئی چین، مکانیسم تغییر شکل و نفوذ منطقه از سنگ دیوار در حالت روباز به زیرزمینی با شیب بالا با استفاده از آزمون مدل فیزیکی و شبیه سازی عددی مورد مطالعه قرار گرفت . در مرحله اول، بخش نمونه انتخاب شده از پژوهش تعمیم داده شد. مدل فیزیکی با مواد مشابه ساخته شده است. روش خاص برای شبیه سازی عمل معدن، شماره گیری شاخص ها و اندازه گیری دوربین های دیجیتال برای نظارت بر تغییر شکل مدل در طول کل فرآیند استخراج استفاده شد. در مرحله دوم، مدل های عددی ساخته شده و عمل استخراج با استفاده از نرم افزار شبیه سازی عددی به منظور بررسی نتایج حاصل از آزمایشات مدل فیزیکی شبیه سازی شده است. نتایج نشان می دهد که شکست نهایی از سنگ دیوار در مناطق نزدیک شدن به بدن سنگ به نظر می‌رسد و نفوذ زیادی در ثبات شیب زیرزمینی ندارد. جابه‌جایی سنگ دیوار از مدل به آرامی با افزایش عمق معدن افزایش می‌یابد. قوانین تغییر جابه‌جایی سنگ نزدیک شدن به گسل مشابه با سنگ دیگر در همان عمق است؛ نتایج حاصل از آزمون مدل فیزیکی به طور کلی با شبیه سازی عددی توافق دارد.

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