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Physical Modelling of Caving Propagation Process and Damage Profile Ahead of Cave-Back

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Abstract

The cavability assessment of rock mass cavability and indicating the damage profile ahead of a cave-back is of great importance in the evaluation of a caving mine operation, which can influence all aspects of the mine operation. Due to the lack of access to the caved zones, our current knowledge about the damage profile in caved zones is very limited. Among the different approaches available, physical modelling can provide a useful tool for assessment of the cave propagation and understanding the cave-back mechanism. Despite the general belief of the continuous damage profile ahead of a cave, the recent studies have shown a different mechanism of banding fracture. In order to investigate the caving mechanism ahead of a cave, a base friction apparatus is designed in this work. The base friction powder is used as the modelling material for physical testing, where its strength properties is significantly dependent on its unit weight. The effects of the material's unit weight and the undercutting process on the cavability and cave-back height are studied. The experimental results undertaken in this research work clearly confirm the banding fracture mechanism in the caved zone, rather than continuous yielding. The effect of the undercutting sequence on the cave-back height is investigated through three different scenarios of symmetric undercutting with a gradual increase in span, symmetric undercutting with a sudden increase in span, and asymmetric undercutting. The results obtained show that the ground deformation is significantly dependent on the undercutting sequence, where choosing a greater undercutting span results in a faster cave propagation and smaller accessible undercut spans.

1. Introduction

A significant increase in the human need for minerals, due to the progress of societies and industrialization, has propelled the mining industry to extract deep, low grade, and massive ore deposits. There has been a considerable increase in the ore production demands, especially in the recent years, (see Figure 1), which has resulted in the special interest of the mining investing sector for the caving and super-cave mining methods. The block caving method, as one of the main mass mining methods, has attracted special attention in the recent decades due to the high production rate, low operating costs, high safety, and high mechanised ability [1, 2].

In the block caving method, the undercut is created by extracting tunnels underneath the orebody followed by drilling and blasting of rock slices. By removing the broken materials from the production level, void is created. Gravity and tectonic stresses lead to the collapse of roof and propagation of the cave. The cave is required to propagate upward till reaching the ground surface or a previously caved level.

One of the limiting issues in understanding the block caving mechanism is the lack of access to the orebody. Our access is only limited to the undercut and extraction levels, and there is no way to visually inspect the caved zone, which restricts our

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knowledge regarding the rock mass state in the caved column and the caved back location. Therefore, the implementation of risk mitigation measurements and imminent risk identifications are limited, which may result in uncontrolled large-scale dynamic events. Hanging up of the cave-back, poor fragmentation, and undesirable cave propagation outward of orebody that leads to ore dilution are other consequences of the lack of access [4-6].

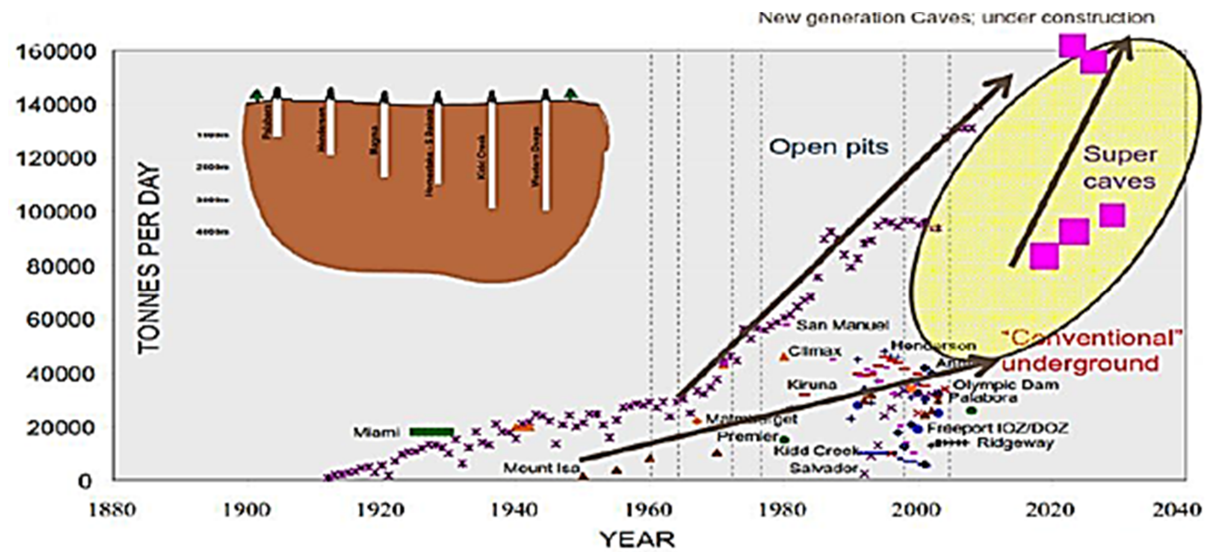


Figure 1. Production capacity in different mining methods [3].

Cavability is the most important parameter involved in the design of a caving mine, which determines that a deposit can be mined or not. The damage ahead of the cave-back is another important parameter involved in the design of a caving mine. These two factors have significant influences on the other aspects of a caving mine such as designing undercut, extraction level, draw points, supports, and draw strategy [7]. The design of super-caves and extraction of large amounts of ore deposits from these underground structures is not feasible unless a precise cavability assessment is carried out and the damage profile ahead of the cave-back is being determined. The inappropriate estimation of these factors can lead to several problems where, in the worst case, it can lead to the failure of the project [3]. Most of the previous studies have been carried out on the assessment of cavability [8-12]. As the access to the cave is not feasible, the design, instrumentation, modelling program, and our interpretation are relied on the conceptual model of cave propagation. The Duplancic model [13, 14] is the most widely used and accepted conceptual model in the industry. Duplancic and Brady [13] have presented a conceptual model for the cave damage zones. This model is a combination of analytical, empirical, and numerical methods. The model is based on a case study in Northparkes E26 lift1, NSW Australia, in combination with a numerical model and a seismicity analysis. Based on this model, the cave-back can be characterized into five regions; namely, the elastic, seismogenic, yielded, air gap, and mobilized zones, as shown schematically in Figure 2. An important aspect of this model is the boundaries between the regions where the damage profile ahead of the cave-back is assumed continuous. This means that with an increase in distance from the caved materials, the rock mass damage is continuously decreased. For interpretation of this model, Brown [7] has stated that the boundaries between these regions are diffuse rather than being sharp, and the rock mass undergoes a gradual reduction in strength from the *in situ* state to the caved state.

After the development of this model, it has been widely accepted in the mining industry. However, this model has several shortcomings. A simple linear elastic model has been used to develop the numerical model, and no seismic instrumentation was utilized to record the seismic data behind the cave-back, due to the inaccessibility of the investigated area. Thus the calibration of the numerical model has just been carried out using a simple seismicity analysis [13, 14].

Despite the lack of observations and the limited number of seismic monitoring for development of the Duplancic model, a few examples are available from the failure process in caving mines. Heslop [16], by conducting visual observations in the previously cut and fill stopes above the undercut level in Shabanie Mine, has observed horizontal tensile fractures above the cave-back. He also observed shear displacement and dilation on discontinuities in the periphery of the cave. Panek [17] has observed parallel tensile fractures tangential to the cave boundary through an extensive monitoring at the San Manual mine. Szwedzicki *et al*. [18] used time domain reflectometry (TDR) at the Freeport cave to track the cave propagation and found a cyclic cave failure that showed a discontinuous damage profile. Carlson and Golden [19] also used the TDR monitoring system in the Henderson's 7210 cave and identified multiple tensile cracks parallel to the cave face. Furthermore, there are some observations in open stopes where parallel tensile fractures ahead of cave-back have been identified [20, 21].

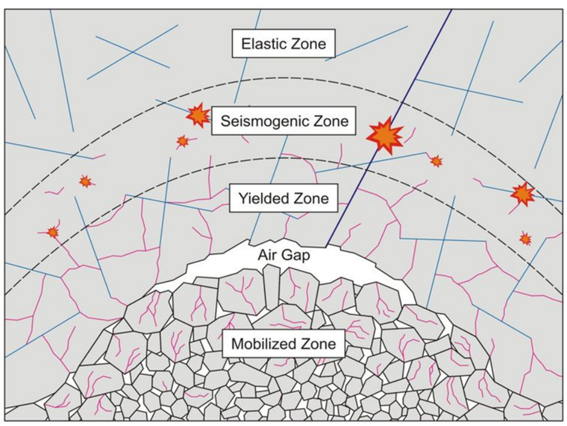


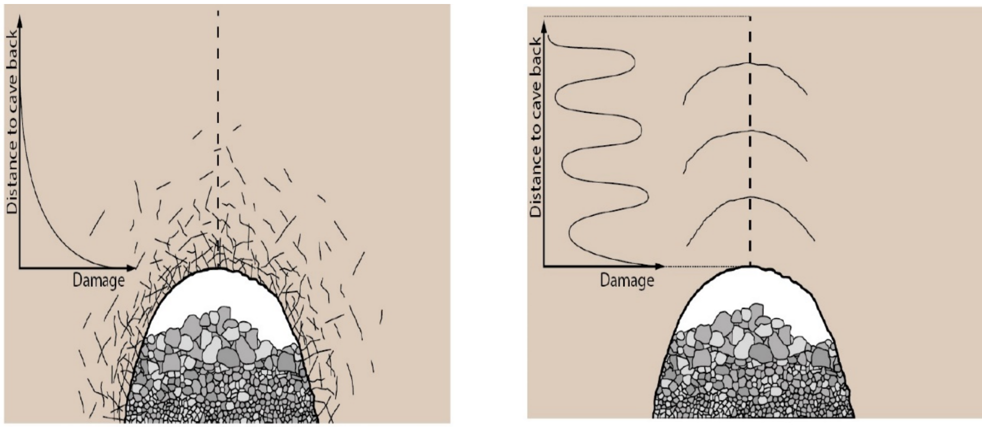
Figure 2. Conceptual model of caving zones [15].

In a number of studies, the S:P wave energy ratio of the micro-seismicity data has been employed to identify the dominant failure mechanism in the cave-back [22-32]. Some of these studies have found the predominant shear mechanism along the pre-existing discontinuities, while the others have found the tensile mechanism.

Some efforts have been undertaken to numerically investigate the failure mechanism and stress regime around the cave. However, the observed failure mechanism of the numerical models is directly dependent on the type of numerical code (continuum or discontinum) and the employed constitutive model, and they must be validated through other means [33-36]. Vyazmensky *et al*. [37], using a 2D combined continuum/discontinum code ELFEN, have simulated a generic block caving model, and a clear discontinuity in the damage ahead of the cave has been observed. Reyes-Montes *et al*. [29] have simulated the Northparkes E26 mine using synthetic rock mass (SRM) in PFC3D, and have observed tensile cracking of bonds at the onset of fracturing. Lisjak *et al*. [38] by using Y-Geo, a hybrid FEM/DEM code, have observed a series of fractures parallel to the cave zone. Li *et al*. [39] have used a finite element code, RFPA2D, to observe the surface subsidence in block caving. They observed a series of pressure balancing arches and stress released zones in different levels of the cave back. Garza Cruz and Pierce [40] have employed 3DEC to simulate the caving condition, finding that vertical stresses at the cave back decrease, while the sub-parallel tensile fractures are generated, and progressive spalling is shed upward.

Physical modelling can provide a very useful tool to understand the complicated mechanism of excavation in geo-material under both the 1g [41] and centrifugal loading conditions [42, 43]. The physical modelling can be divided into 3D and 2D models. The 3D physical models are usually very expensive, time-consuming, and very hard to run. However, the 3D models can be simplified into 2D models with some assumptions that make them much easier to run. The use of physical modelling in the caving research works has been very limited, and most of these experiments are concentrated on the study of gravity flow and draw control. A few physical models can be found in the literature, where the caving process and failure mechanism have been discussed. McNearny and Abel [44] by using a 2D model consisting of bricks, have studied the draw point strategy. More recently, Cumming-Potvin *et al*. [45, 46] have carried out a series of centrifuge tests to explain the discontinuous profile damage of the cave-back. Based on their experiments, the banding fracture model has been introduced, which demonstrates a series of jumped fractures parallel to the cave-back, which is in contrast with the conceptual model of Duplancic. The differences in the profile damage of the continuous and banding fracture models are schematically illustrated in Figure 3.

In this work, we aimed to study the cave mechanism and profile damage ahead of the cave-back using physical modelling. To this end, a new base friction apparatus was designed, and the effects of the material's unit weight and the undercutting process on the cave propagation mechanism were investigated.



a) Continuous yielding model *b) Banding fracture model*

Figure 3. Illustration of damage profile conceptual models [46].

2. Materials and methods

One of the main challenges in physical modelling, especially for the rock engineering problems, is to reproduce the real filed conditions in the laboratory. In order to achieve the prospect behaviour of rock masses and for the demonstration purposes, simplifications may be applied [47]. In order to simulate the caving process in this work, a base friction apparatus was designed and constructed.

2.1. Modelling material

In the previous studies, different mixtures of materials have been used for physical modelling. Goodman [48] has used a mixture of flour, cooking oil, and sand in his experiments. Nishida *et al*. [49] have made their physical model using a mixture of BaSo4, ZnO, and vaseline oil (mass ratio of 70:21:9, respectively), calling it the *base friction powder*. This powder has gained a global acceptance for physical modelling so far [50-54]. Therefore, the base friction powder was selected as a modelling material in this work. The base friction powder can be compacted to form solid blocks. The compressive pressure applied on the powder to create solid blocks controls the final unit weight and the corresponding strength of the blocks. The relation between the applied compressive pressure and the unit weight of the compacted base friction powder is shown in Figure 4.

In order to study the influence of the strength properties of materials on their cavability, a series of physical models at different unit weights of 16, 19, and 21 kN/m^3 (the corresponding applied pressure to generate these models are indicated in **Fig. 4**) were conducted, and the cavabilities of these models were compared. The details are presented and discussed in the following section.

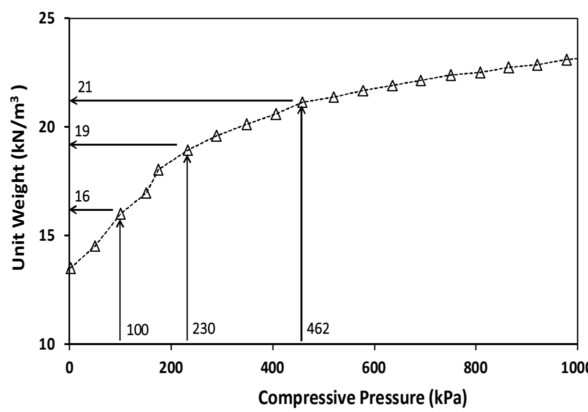


Figure 4. Relation between the applied compressive pressure and the unit weight of compacted base friction powder.

2.2. Mechanism of base friction table

The principles of the base friction table was initially developed by Goodman [48], where the earth gravity was simulated by frictional force acting between a moving frictional base and the model. This machine has been widely used for physical modelling of progressive slope failures. Nishida *et al*. [49] have developed a base friction apparatus to study the sinkhole propagation in Japan. The similarity of mechanisms between the sinkhole propagation and the cave propagation zones was a great motivation in this study for application of the base friction table for simulating the caving process and damage profile ahead of the cave-back.

The developed base friction apparatus of this study is schematically illustrated in Figure 5. The apparatus has an endless base belt, moving on a stiff metal base plate. The movement of the base belt, along the Y axis, is controlled by rotation of drive shafts that are connected to an electric motor.

The principle is to convert the vertical profile of the underground mine into a planar model. The ground model with a thickness of 30 mm was prepared on the base belt having a desired strength, and an undercut span was excavated. In order to achieve a plane strain condition, the strain of the model perpendicular to the table surface (Z axis shown in Figure 5) must be restricted; therefore, the surface of the model was confined by means of a Plexiglas plate.

In the base friction table, the displacement of the ground model is restricted, and by the movement of the base belt, a frictional force F is appeared between the base belt and the ground model for a unit contact area. This frictional force can be calculated as:

$$F = \gamma_m . t . \mu \quad (1)$$

where,

F is the frictional force between the base belt and the ground model for a unit contact area;

γ_m is the unit weight of the model material;

t is the thickness of the model;

μ is the friction coefficient between the model and the base plate.

According to He *et al*. [55], in simulation of the gravitational stress in the model using the applied force F, the thickness of ground model should be limited as the gravity would act at the centre of the model, while the applied force F acts on all points of the model.

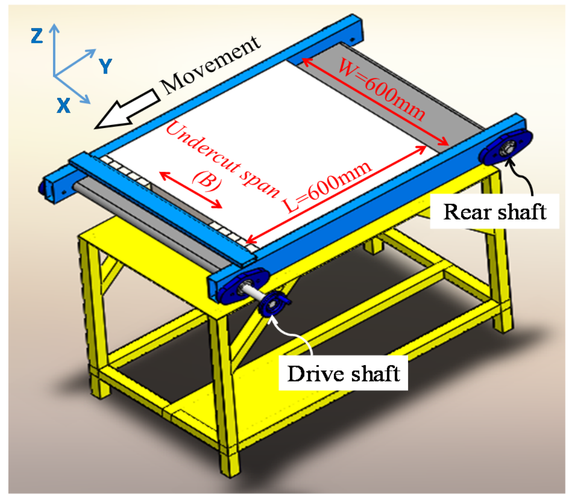


Figure 5. A schematic view of the base friction apparatus.

Rigid blocks were placed in front of the model as pillars (see Figure 6), where the process of undercutting was simulated by removal of the blocks. For each step of undercutting, the base belt was moved under a steady speed until the cave back reached a stable height, as illustrated in Figure 6 (b).

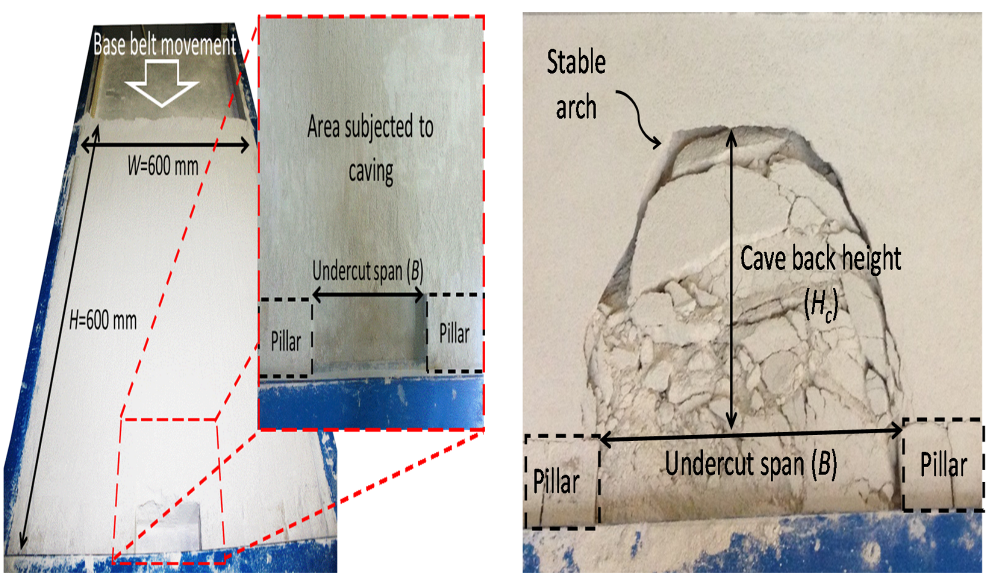
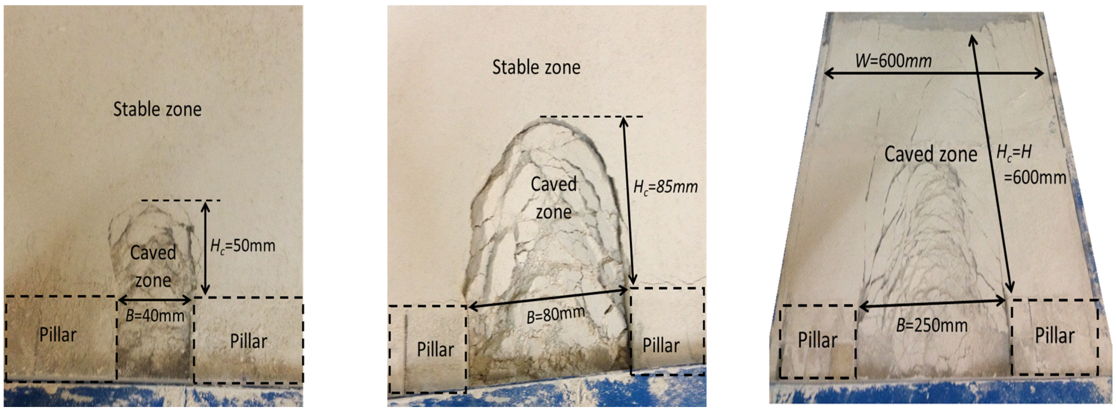


Figure 6. Typical model characteristics and parameter definition, a) Prepared model with a single undercut span, b) Failure occurring due to base belt movement

3. Results and discussion

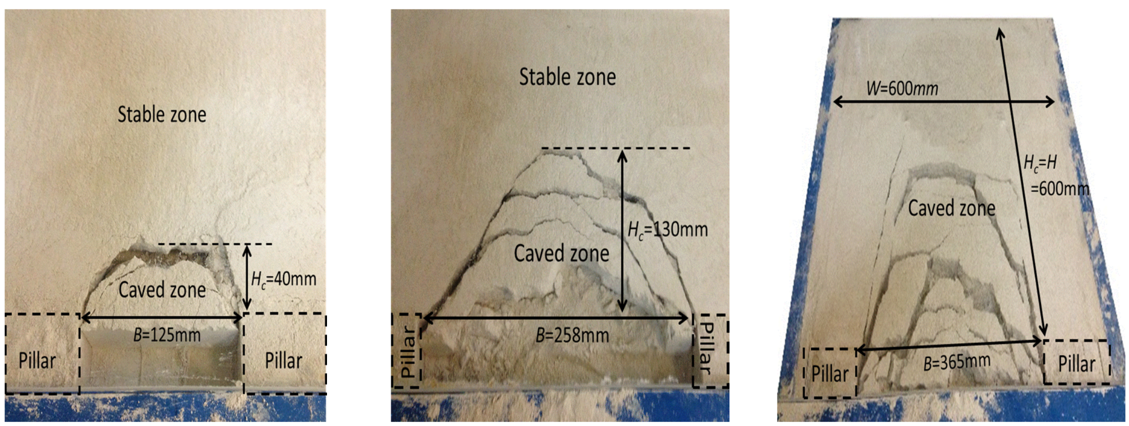
3.1. Materials and cavability

As noted earlier, the physical models having three different unit weights of 16, 19, and 21 kN/m^3 were prepared to study the effect of unit weight and strength of material on the caving mechanism. In each model, the undercut span (B) was varied at several steps, where the base belt was moved continuously until a stable arch was reached at each undercutting span. The height of this arch was recorded as a cave-back height (H_c). The failure mechanisms for these models at different undercut spans are illustrated in Figures 7-9.



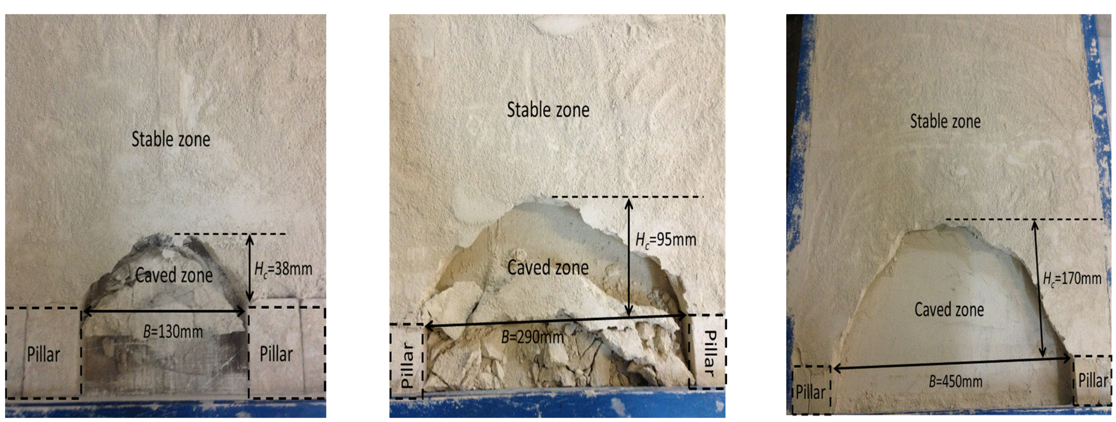
a) B = 40 mm   b) B = 80 mm   c) B = 250 mm

Figure 7. Symmetric undercutting with a gradual increase in span (γ = 16 kN/m^3).



a) B = 125 mm   b) B = 258 mm   c) B = 365 mm

Figure 8. Symmetric undercutting with a gradual increase in span (γ = 19 kN/m^3).



a) B = 130 mm   b) B = 290 mm   c) B = 450 mm

Figure 9. Symmetric undercutting with a gradual increase in span (γ = 21 kN/m^3).

The cave-back height (H_c) as a function of undercut span (B) is illustrated in Figure 10. It could be seen that for the unit weights of 16 kN/m^3 and 19 kN/m^3, the maximum possible undercut spans with stable cave-backs were 200 mm and 330 mm, respectively. For the undercut spans beyond these values, the cave-back reached the ground surface (top of the model). For the unit weight of 21 kN/m^3, a stable cave-back was formed and the caved zone did not reach the ground surface.

In order to investigate the effect of unit weight on the size of cave-back, the cave-back heights were normalized by their corresponding undercut spans (H_c/B) and plotted as a function of material unit weight in Figure 11. It was observed that as the unit weight of the model increased, the normalized cave-back height decreased. The observed trend indicates that at very high values of the unit weight, the cave-back height reaches zero. This may happen in underground caverns inside very strong rock masses, where the roof of the cavern is stable without formation of any plastic zone around the cavern. On the other hand, at low values of the unit weight, the cave-back height increases dramatically. This means that for a very loose material, no stable cave-back can be expected, and the material will flow into the excavated area, even at small undercut spans.

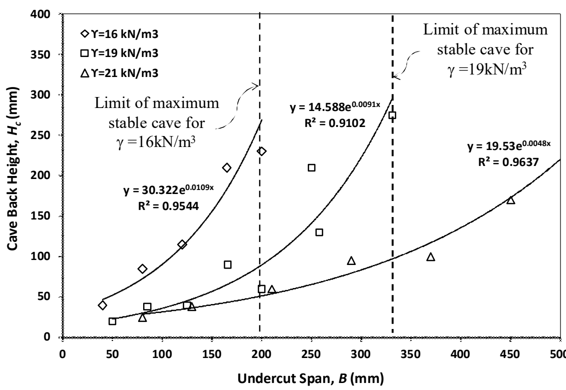


Figure 10. Cave-back height as a function of undercut span.

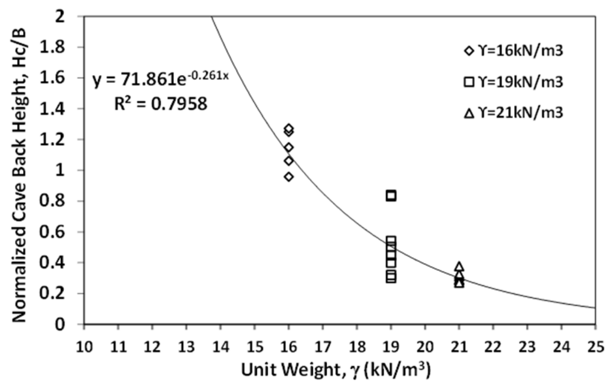


Figure 11. Cave-back height as a function of unit weight.

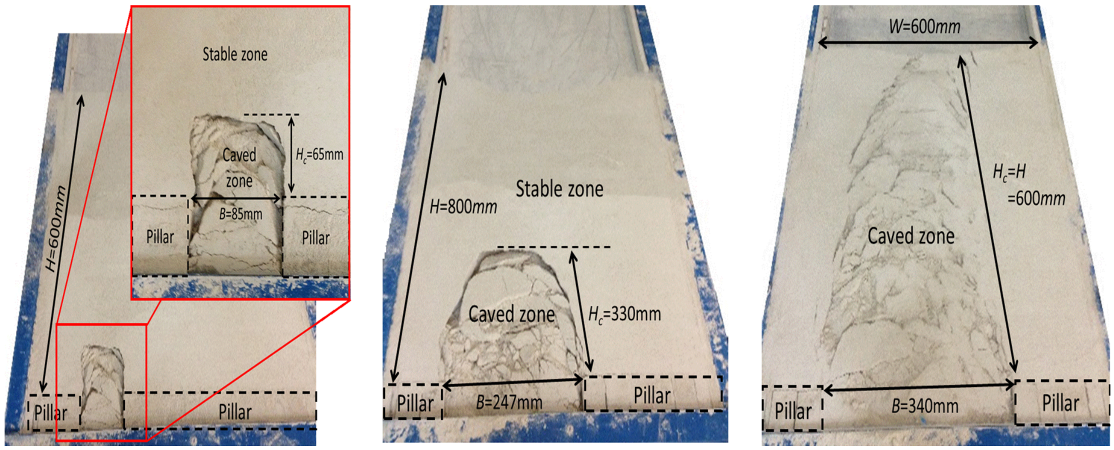
3.2. Undercutting process and cave propagation

The results of the previous section show that at the unit weight of 19 kN/m^3, a stable cave-back is formed for a small undercutting span, while the cave-back reaches the ground surface at a wide undercutting span. Therefore, the unit weight of 19 kN/m^3 was chosen to study the effect of the undercutting process on the cave propagation mechanism. To this end, three different processes were investigated.

Process 1: symmetric undercut with a gradual increase in span. In this process, the undercutting was started with a narrow span in the centre of the model, and the base belt was moved until a stable cave-back was formed. Then the undercut span was increased symmetrically. This process was continued until the cave-back reached the ground surface. It is noteworthy that the model results presented in the previous section were conducted under this undercutting strategy. The cave propagation under this process is illustrated in Figure 8.

Process 2: symmetric undercut with a sudden increase in span. This scenario was similar to the first scenario with the difference that the undercutting was carried out using a greater span size. The undercutting was continued until the caved zone reached the ground surface.

Process 3: asymmetric undercut with a gradual increase in span. In this process, the undercutting started with a narrow span from one side of the model, and the base belt was moved until a stable cave-back was reached. Then the undercut span was increased asymmetrically, and the process was repeated until the cave-back reached the ground surface. The cave propagation under this process is illustrated in Figure 12.



a) *B* = 85 mm b) *B* = 247 mm c) *B* = 340 mm

Figure 12. Asymmetric undercutting (γ = 19 kN/m³).

The results of this work clearly show that the profile damage ahead of the cave-back, in all of the three scenarios, is not continuous but the damage zones in the bands parallel to the cave-back are observed. Therefore, these results confirm the banding fracture theory of Cumming-Potvin [23].

The cave-back height as a function of undercut span for the different scenarios of undercutting is illustrated in Figure 13. It can be clearly seen that for a specific undercut span, there is no abrupt difference between the cave-back heights under different undercutting processes. However, in undercutting process 2, where the total undercut span was created at one step, the maximum sable cave-back was generated at the undercut span of 200 mm. This stable undercut span is approximately half of the maximum undercut span in the other two scenarios. These results confirm that the model deformation is mostly dependent on the undercutting span, rather than the undercutting location. When the ground is undercut suddenly with a wide span, rather than increasing the span gradually, the *in situ* stresses have less time to redistribute in a supportive pattern, resulting in a smaller stable undercut span.

A comparison between the undercutting processes 1 and 3 show that the model behaviour is independent from the location of undercutting. It means that in a caving process, the undercut span can be increased symmetrically or asymmetrically, depending on the technical and economic conditions and safety, without having influences on the cave propagation.

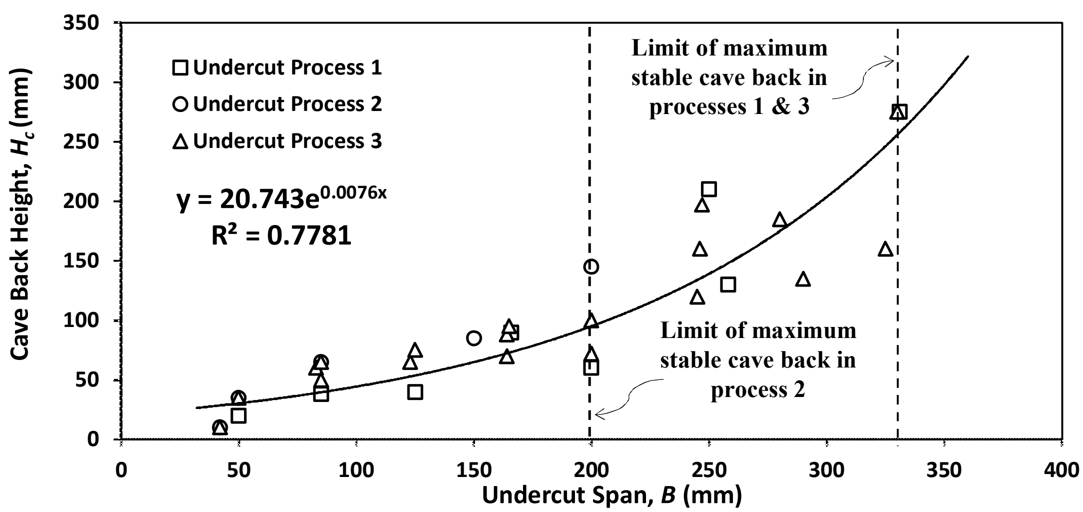


Figure 13. Effects of undercutting processes on the cave-back height.

4. Conclusions

Our current knowledge regarding the cave propagation and the damage profile ahead of caves is very limited due to the lack of access to the caving zones. The most widely accepted model of the cave propagation zone is the Duplancic model, which assumes continuous yielding of the caved zones. In this work, the mechanism of caving propagation and the damage profile ahead of the cave-back were studied using physical modelling. To this end, a base friction table was designed, and ground material was simulated using the base friction powder. Through an extensive series of experiments, a suitable unit weight of base friction powder was selected to create a stable cave at small undercutting spans as well as unstable model at large spans. The effect of the undercutting strategies on the cave-back height was investigated through three different scenarios of symmetric undercutting, systematic undercutting with increased undercutting span, and asymmetric undercutting. The results obtained show that the model deformation is mainly controlled by the undercutting span rather than the undercutting location. When the ground is undercut suddenly with a wide span, the *in situ* stresses have less time to redistribute in a supportive pattern, resulting in a smaller stable undercut span. It was found that the systematic and asymmetric undercutting did not significantly alter the cave-back height, and the chosen undercut span could change the stress distribution and stable cave height. The results obtained from this work clearly showed that the banding fracture mechanism was the dominant caving mechanism, while there was a debate in the previous studies regarding the continuous or discontinuous nature of the caving zones.

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مدل‌سازی فیزیکی فرآیند گسترش تخریب و پروفایل ناحیه آسیب‌دیده در پشت طاق تخریب

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چکیده:

دانستن اطلاعات دقیق از تخریب پذیری کانسنگ و همچنین چگونگی پیشرفت تخریب در پشت طاق تخریب، در معادن تخریبی از اهمیت بسیار بالایی برخوردار است به‌گونه‌ای که تمام وجوه عملیات معدنکاری را تحت‌الشعاع قرار می‌دهد. با توجه به مشکلات دسترسی و ابزاربندی دقیق در پشت طاق تخریب، اطلاعات چندانی در مورد چگونگی پیشرفت تخریب و گسترش آن در امتداد کانسنگ در دست نیست. در میان تمامی روش‌های موجود برای بررسی گسترش تخریب، مدل‌سازی فیزیکی روشی است که می‌تواند به‌خوبی چگونگی شروع، گسترش و مکانیسم تخریب را به نمایش بگذارد. برخلاف تصور پذیرفته‌شده در بین عموم معدنکاران در مورد پروفایل شکست پیوسته در معادن تخریبی، مطالعات اخیر مکانیسم جدیدی به نام شکست باندی را نشان داده است. در این نوشتار به‌منظور تحقیق در چگونگی گسترش تخریب، دستگاه میز اصطکاک پایه طراحی شد و به‌منظور مدل‌سازی فیزیکی با این دستگاه از موادی به نام پودر پایه که خصوصیات مقاومتی آن وابسته به وزن مخصوص این ماده است، استفاده شد. اثرات وزن مخصوص مواد و همچنین فرآیند زیر بری بر تخریب پذیری و همچنین گسترش طاق تخریب بررسی شد. نتایج تست‌های فیزیکی، مکانیسم شکست باندی را به‌جای پروفایل شکست پیوسته به‌خوبی نمایش می‌دهد. همچنین تأثیر مراحل زیر بری بر ارتفاع طاق تخریب در سه روش مختلف زیر بری متقارن با افزایش تدریجی دهانه، متقارن با دهانه یکجا و زیر بری غیرمتقارن بررسی شد که نتایج حاکی از آن بود که تغییر شکل در مدل کاملاً وابسته به مراحل زیر بری است و هرچه دهانه زیر برش بزرگ‌تر باشد درنتیجه طاق تخریب سریع‌تر پیشروی می‌کند.

کلمات کلیدی: مدل‌سازی فیزیکی، معدنکاری تخریبی، تخریب پذیری، شکست باندی، پروفایل تخریب.