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Experimental investigation of undercut stratified rocks using base friction technique

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Abstract

Excavation inside stratified rocks can be for mining purposes or construction of civil underground spaces. In coal mines, coal layers are usually placed between other layers of sedimentary rocks. One of the most important factors affecting the stability of the tunnel as well as the shape of the collapsed area above the tunnel is the angle of the layers. In this research, the influence of the bedding slope angle on the instability and failure mechanism in undercut inclined stratified rocks was investigated experimentally. 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. For this purpose, a total number of 20 physical model tests were conducted and the undercut process and the instability of the roof layers was modelled using a basic friction table, while a base friction powder was used as a modelling material. The results of this research show that in the case of horizontal stratified rocks, the length of the failed roof beams decreases from the bottom to the top, while in the case of inclined layers, the length of the beams increases from the bottom to the top, so that the longest beam is placed in the highest part of the unstable area. Also, increasing the span of the tunnel does not affect the shape of the collapsed area and only the area of the collapsed area increases and the amount of this increase is linearly related to span of the tunnel. Also, the 30 degree angle has the lowest and the horizontal mode has the most collapsed area at the top of the tunnel.

Keywords

Stratified rocks, Physical modelling, Base friction table, Undercut span.

1 Introduction

Given that many underground structures such as civil and mining tunnels are constructed in stratified rock masses, a proper understanding of the behaviour of such rock masses will play an important role in analysing the stability of these structures. Stratified rock masses are usually of sedimentary or metamorphic origin. These rock masses have acquired their layered structure by sediment deposition or by schistosity during metamorphism. Many researchers have studied the behaviour of stratified rock masses in tunnelling (Brady & Brown 1993; Diederichs & Kaiser 1999; Stille & Palmstrom 2008; Hoek & Marinos 2009; Fortsakis et al. 2012).

Common features in all types of stratified rock masses include the continuous discontinuity between layers, the almost uniform spacing of the layers, and their almost identical orientation. A typical example of such a rock mass is shown in Fig. 1.

Many researches have been done on investigating horizontal stratified rocks and their failure mechanism under excavation, but the inclined stratified rocks are rarely investigated. Among the different approaches available, physical modelling can provide a useful tool for understanding the rock failure mechanisms. Among the physical modelling techniques, the base friction table is a very innovative and attractive method. The principles of the base friction table was initially developed by Goodman (1976), 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 failures (Moussaei et al. 2019; Heydarnori et al. 2020; Alipenhani et al. 2024).

In this study, using a base friction table, the effect of the layers inclination angle and the undercut span on the stability of the excavation space, the failure mechanism, and the failure height were evaluated.

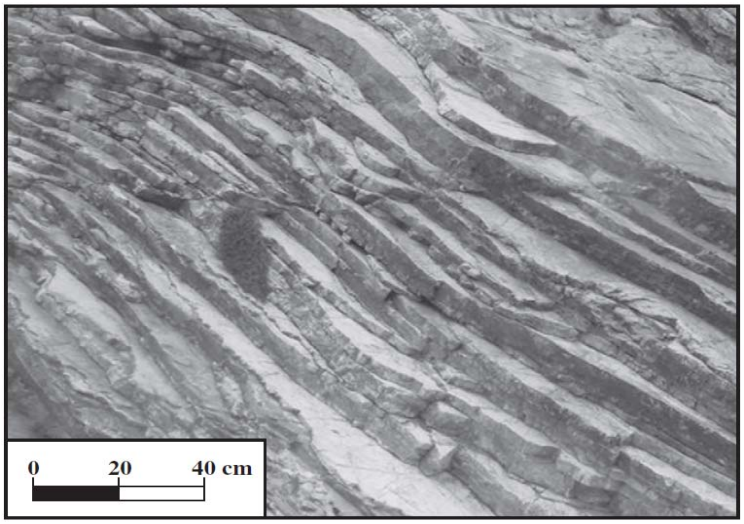


Fig. 1 An example of a limestone stratified rock mass (Fortsakis et al. 2012).

2 Physical modelling

2.1 Base friction table

A picture of the base friction table used in this study is shown in Fig. 2. The apparatus has an endless base belt, moving on a stiff metal base plate. The movement of the base belt is controlled by rotation of drive shaft. The principle is to convert the vertical profile of the underground mine into a planar model.

The ground model was prepared on the base belt having a desired strength, and an undercut span was excavated. 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 follows.

$$F = \gamma m.t.\mu \quad (1)$$

Where, F is the frictional force between the base belt and the model for a unit contact area, γm is the unit weight of the model material, t is the thickness of the model and μ is the friction coefficient between the base belt and the model.

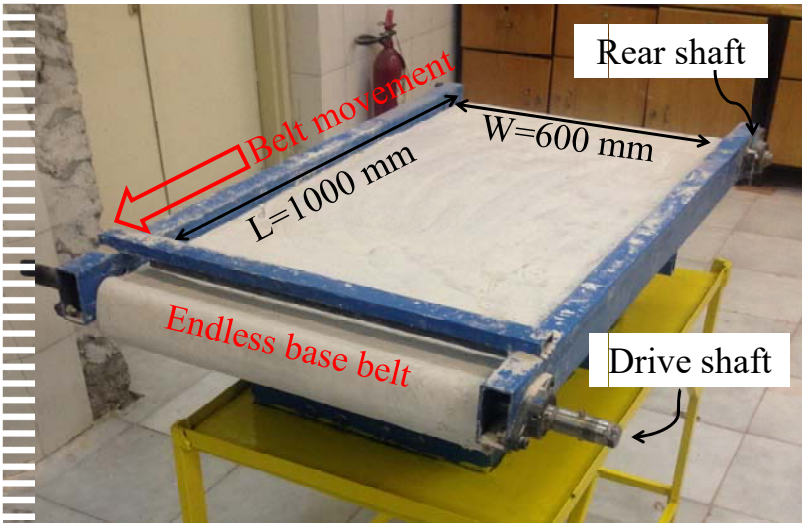


Fig. 2 The base friction table used in this study.

2.2 Modelling material

Goodman (1976) introduced a special powder for physical modeling on base friction table, known as "base friction material". This material is a mixture of flour, cooking oil, and sand. This materialis repeatedly used for physical modelling and was highly regarded for this purpose (Egger 1983; Aydan & Kawamoto 1992; Amini et al. 2015; Amini et al. 2017). By compressing this material inside a mold under an appropriate pressure, solid blocks with desired strength could be made (Amini et al., 2017). A picture of the base friction material, the mold and some beams, produced by this material, is shown in Fig. 3.

Evaluation of physical models requires proper measurement of physical and strength properties of the modeling material. Therefore, those properties of the base friction material, used in this study, were measured. The changes in unit weight of the base friction material as a function of pressure applied to the mold are illustrated in Fig. 4. It can be seen in this figure that by increasing the pressure applied on the mold, the unit weight of the material is increased, however the rate of increment is gradually decreased. The target unit weight of 21.1 kN/m^3 was reached under a pressure of 460 kPa. The uniaxial compressive and tensile strengths of this material were measured 52.5 kPa and 14 kPa, respectively.

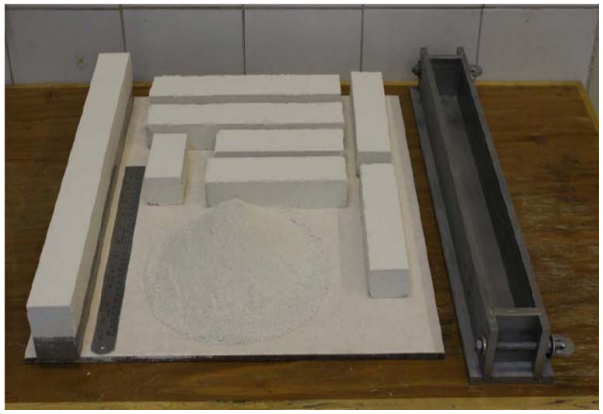


Fig. 3 Base friction material, mold and some solid beams produced by the material (Amini et al. 2017).

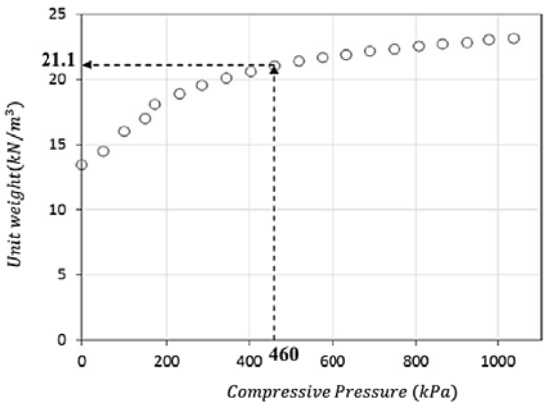


Fig. 4 Unit weight of modeling material as a function of pressure (Amini et al., 2017).

2.3 Loading simulation

In all the physical model tests, the dimensions of the model were fixed and equal to 1000mm×600mm (Fig. 2). The sides and bottom of the model were restrained.

The simulation of the load on the layers and the tunnel was done by slow rotation of the conveyor belt. The loading process was continued by belt rotation until a failure were observed on the model. The loading process were simulated for five different undercut spans (B) and four different layer dip angles (α). Therefore a total number of 20 model tests were conducted in this study. The failure heights measured for each test are listed in Table 1.

Table 1. Maximum failure height measured as a function of layer dip angle and undercut span.

		Undercut span (mm)				
		B=200	*B*=250	*B*=300	*B*=350	*B*=400
Layer dip angle (degree)	*α*=0	0	0	0	320	400
	α=30	0	100	130	145	160
	α=45	0	135	175	220	260
	α=60	0	120	220	280	360

3 Discussion

The failure height as a function of the layer inclinations and undercut span is illustrated in Fig. 5. As is clear from this figure, in general, and regardless of the inclination angle of the layers, the height of the failure zone in the model increases with increasing the undercut span. However, with the exception of models with horizontal layering, the rate of increase in the height of the failure zone increases with increasing layers inclination.

The modes of failures observed in physical models with an undercut span of B=350 mm for different layer inclinations are shown in Fig. 6. It is obvious from this figure that the mode of failure is a function of layer inclination. For horizontal layers, because the layers are supported in both sides, no failures observed for undercut spans less than 350 mm (Table 1). However, when a failure occurred in the model with horizontal layers at B=350 mm, a big failure height were observed, compared to other inclinations (see Fig. 6-a). Except for the models with horizontal layers, the layers act as cantilever beams and the failure zone had a triangle shape, where the height of the collapsed zone increased by an increase in layers inclination.

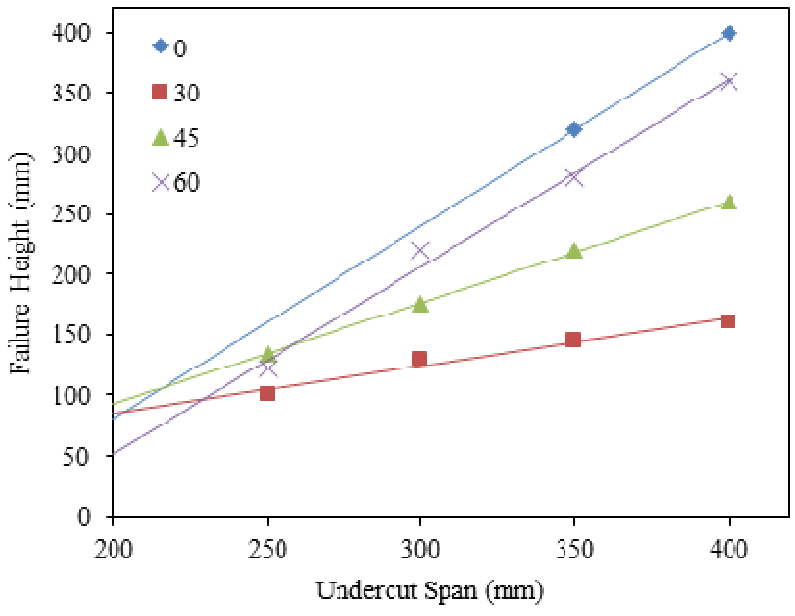
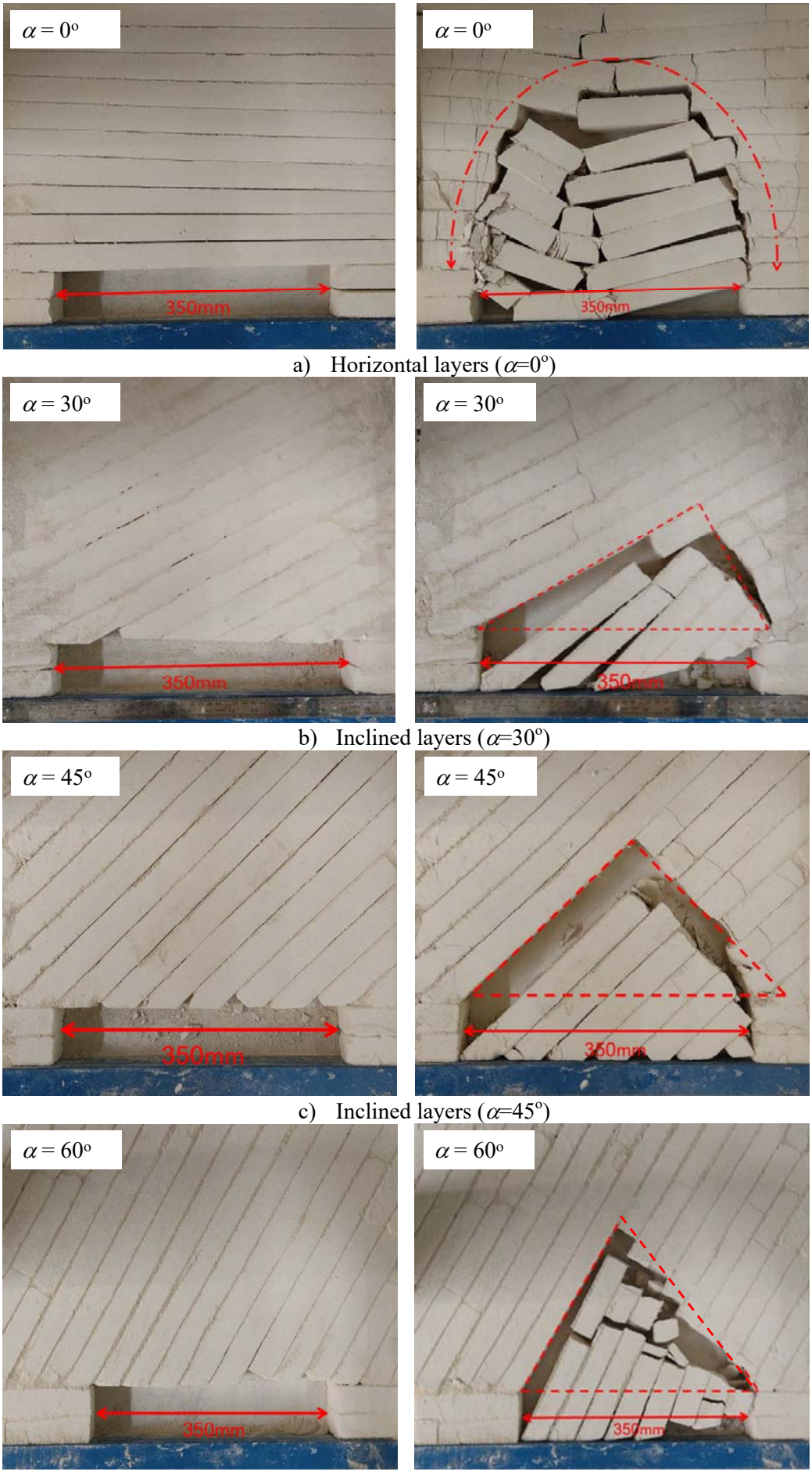


Fig. 5 The failure height versus undercut span for different layer inclinations.



a) Horizontal layers (α=0°)

b) Inclined layers (α=30°)

c) Inclined layers (α=45°)

d) Inclined layers (α=60°)

Fig. 6 The failure modes in models with an undercut span of B=350 mm for different layer inclinations.

4 Conclusion

In this study, a series of small scale physical models was conducted and the undercut process and the instability of the roof layers was modeled using a basic friction table, while a base friction powder was used as a modeling material. Using this powder, rock layers were constructed where their density was controlled by compaction degree of the powder. The undercut span was extended gradually while the crack initiation and propegation in the roof beams was monitored by means of an image processing setup. Based on the modeling results, it was determined that the rock layers act as double-ended beams in horizontal layers, while they act as cantilever beams in inclined layers. As a result the horizontal layers had greater resistance to failure, compared to inclined layers. For this reason, the maximum stable span in the models with horizontal layers was 300 mm, while in models with inclined layers this span was reduced to 200 mm. In addition, In the case of horizontal layers, the first cracks are formed in the middle of the lower surface of the roof beams and propegates upwards, while in the inclined layers, the beams generally act as contilever beams, the first cracks initiate at the upper surface of the beam and propegates downward. Therefore, horizontal beams show more bending resistance compared to inclined beams. However, the expansion rate of the failed area in horizontal stratified rocks is higher than in inclined rock layers, and the largest failed area, for a specified undercut span, occured in horizontal stratified rocks. Note that the lowest expansion rate of the failed area and the smallest unstable area was observed in inclined layers with a slope angle of 30 degrees, so it seems that this slope angle is the safest for excavation in stratified rocks. Of the limitations of this study is that it ignores parameters such as changes in layer thickness, filler between rock layers, and the presence of groundwater. These parameters require further research and numerical modeling, which is recommended for future studies.

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