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Study of surface subsidence above an underground opening using a trap door apparatus

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ABSTRACT

Physical model simulations have been performed to determine the effects of underground opening configurations on surface subsidence under super-critical conditions. This paper indicates the importance of the main factors that control the extent of subsidence produced on the surface and determines the effects of geometry of underground openings on the angle of draw, the maximum subsidence and the volume of the subsidence trough. A trap door apparatus with the test area of $95 \times 95\ cm^2$ has been fabricated to perform the scaled-down simulations of surface subsidence. Gravel is used to represent the overburden in order to exhibit a cohesionless frictional behavior. In plan view the excavation dimensions are sufficient to induce maximum possible subsidence. The findings can be used to evaluate the subsidence profile for tunnels and caverns in soft ground. The results show that the angle of draw and the maximum subsidence are controlled by the width (W), length (L), height (H) and depth (Z) of the underground openings. The angle of draw and maximum subsidence increase with increasing L/W ratio and tends to approach a limit when L/W equals 3. For the same L/W ratio and H/W ratio, increasing the Z/W ratio reduces the angle of draw and maximum subsidence. The volume of the subsidence trough increases with increasing H/W ratio and L/W ratio. The width of the subsidence trough can be represented by sets of empirical relations. The relation between opening depth and subsidence trough developed by Rankin (for cohesionless soils) is in good agreement with most physical model results for deep openings (Z/W = 2–4), while for Z/W = 1, the predicted trough width is less than the physical model simulation. The volume of the subsidence trough is largest for Z/W = 2.5 and for H/W = 0.6, and is about 60% of volume of the underlying opening.

1. Introduction

Surface subsidence as a consequence of underground mining and tunneling can impact the environment and surface structures within the mine area (Asadi et al., 2005). Sometimes this subsidence is of little importance to green field sites (i.e., those without surface structures), but it may cause significant damage where surface structures are present. However, even without structures, subsidence can do damage. Many scholars have studied the mechanisms of land subsidence caused by groundwater withdrawal (Murayama et al., 1961; Lofgren, 1968; Helm, 1975, 1976; Poland, 1977; Holzer, 1981; Shen et al., 2006). It is widely accepted that the compression of soft clay layers and the compaction of sand is a main cause of land subsidence and time delay of deformation. In the United States, as elsewhere, farm land or urban areas can lose substantial value as a result of land subsidence (Holzer, 1984). In order to minimize the environmental impact, a reliable subsidence prediction is essential. One key parameter for subsidence analysis and prediction is the angle of draw, which defines the limits of the area affected by subsidence. Determination of the extent of surface subsidence due to underground mining is important for deciding whether a particular structure is located within the subsiding area or not. It is known that, for a particular extraction geometry, the area affected by subsidence is controlled predominantly by geologic conditions in the overburden and by the mining geometry, i.e. lateral extent, thickness, depth, and dip of the seam mined.

In practice, it is difficult to determine with certainty the precise extent of mining subsidence and hence the angle of draw. However, the angle of draw can be predicted by observations of the underground openings assisted by analytical solutions, such as the profile function method (Singh, 1992), used to calculate the

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angle of draw from depth of the excavated opening and the boundary of the subsided area for sub-critical and critical subsidence. Yao et al. (1991) introduced an analytical calculation model for the angle of draw by the use of a finite element model proposed by Reddish (1989) at the Nottingham University. They studied the influence of overburden strength and different rock mass properties, and the presence of a distinct bed, on subsidence limit characteristics. Their results show that the angle of draw is related to the overburden properties, depth and configurations of the mine openings.

Physical modeling has played an important role in studies related to stability of underground mines and tunnels. A variety of modeling techniques have been developed all over the world to study ground response to underground excavation and tunneling. These techniques range from the two-dimensional trap door tests to the miniature tunnel boring machines that simulate the process of tunnel excavation and lining installation in a centrifuge (Meguid et al., 2008). Caudron et al. (2006) studied soil-structure interaction during a sinkhole phenomenon using an analog two-dimensional soil and a physical model. They use bidimensional Schneebeli material in a small-scale model allowing fully controlled test conditions. Terzaghi (1936) uses a model, characterized as the trap-door model. According to this model, the deforming arch of a tunnel can be investigated by a downward moving trap-door while the soil above the tunnel can be represented by a layer of granular or slightly cohesive soil. Based on this simple model, the evolution of the mean vertical pressure acting on the trap-door during its downward movement can be studied. The physical model allowed him to represent a case study and to determine it completely with a limited set of parameters.

Empirically derived relationships are one of the principal methods of predicting mining and tunneling subsidence. This technique is based on the experience gained from a large number of actual field measurements. The empirical methods are quick, simple to use, and yield fairly satisfactory results. Fattah et al. (2013) compared the shape of the settlement trough caused by tunneling in cohesive ground by different approaches: analytical, empirical, and numerical. Their study showed that the finite element method overpredicted the settlement trough width compared with the results from empirical solutions of Peck (1969) for soft and stiff clay, but are in excellent agreement with Rankin's (1988) estimation. An empirical profile or influence function method requires knowledge of maximum possible subsidence (S_{max}) or maximum subsidence occurring (S), which is related to S_{max} by a function related to width: depth ratio of extraction (Baghuguna et al., 1991).

The objective of this study is to develop a trap door apparatus for use in three-dimensional simulations of surface subsidence under various underground opening configurations. The investigation is focused on the angle of draw, maximum subsidence and volume of trough as a function of the opening geometry. In this paper, the results are obtained from the overburden simulated by using gravel (cohesive/frictional material). The simulations are under super-critical conditions, i.e. in plan view the excavation dimensions are sufficient to induce maximum possible subsidence. The test results are compared with subsidence profile predictions obtained from empirical methods for tunnels in fractured rock mass.

2. Trap door apparatus

A trap door physical model has been designed to simulate subsidence of overburden in three dimensions and to assess the effect of the geometry of underground openings on the surface subsidence. The physical model (Fig. 1) comprises three main components: the sample container, the mine opening simulator, and the surface measurement system. The sample container is filled with materials, in this case gravel, used to simulate overburden. A custom-made $0.95 \times 0.95\ m^2$ clear acrylic plate with 15 mm thick is placed in the grooves of the square steel frame. Four acrylic sheets are secured with a steel plate at each side. The testing space is $0.95 \times 0.95 \times 0.60\ m^3$. The mine opening simulator is an array of wooden blocks with sizes of $50 \times 50 \times 100\ mm^3$. The wooden blocks are arranged in ten columns with five blocks for each column. Fifty small blocks can be gradually and systematically moved down to simulate underground openings with different geometries and hence inducing the subsidence of the gravel. The mine opening simulator is installed underneath the sample container. The measurement system of the surface subsidence includes a sliding rail with a laser scanner. To measure the surface subsidence under various underground opening geometries, the laser scanner is moved horizontally in two directions. The precision of the measurements is one micron. The results are recorded and plotted as three-dimensional profiles. The maximum subsidence values, angles of draw, slopes and volume of the subsidence trough can be readily determined for each opening configuration.

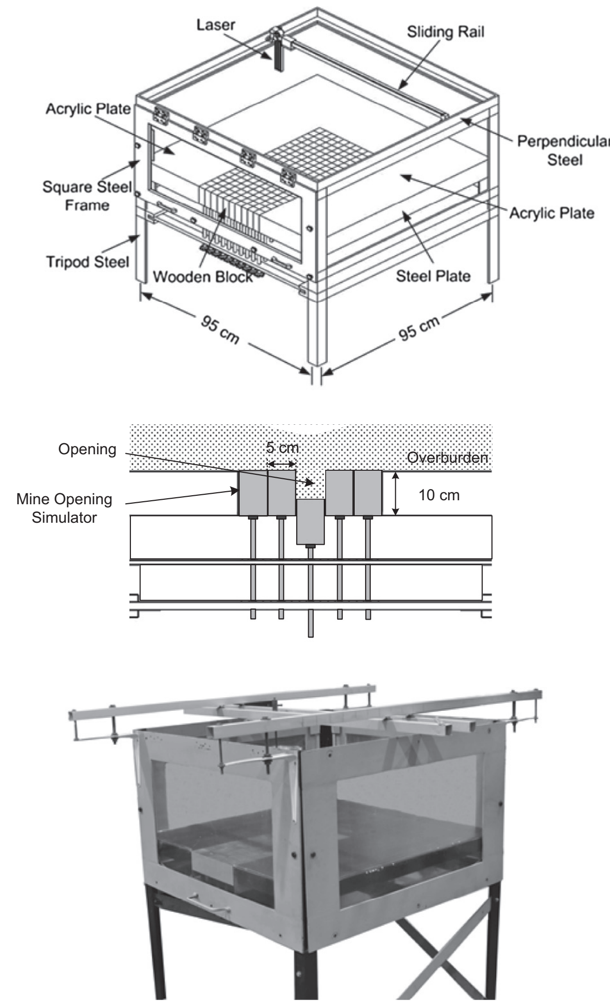

Fig. 1. Trap door apparatus used for physical model testing.

3. Properties of gravel

Clean gravel is used to simulate the overburden in the physical model. The material is subjected to grain size analysis and direct shear testing.