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Development of a spring analogue approach for the study of pillars and shafts

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ABSTRACT

In civil and mining operations that involve ground excavation and support, the loads are distributed between the ground and support depending on their relative stiffness. This paper presents the development of conceptual single-degree-of-freedom models, which are used to derive equations for estimating displacements and stresses for ground-support interaction problems encountered in pillars in room-and-pillar mining (natural support system), and liners for circular vertical shafts (artificial support systems). For pillar assessment, mine-pillar interaction curves can be constructed using a double spring analogy. Additionally, the effectiveness of different support systems can be evaluated depending on their effect upon the mine-pillar system. For shaft design, an initial estimation of the required lining strength and thickness can be readily made based on a double ring analogue. For both problems, the results from the proposed approach compare well with those obtained by finite element numerical simulations.

1. Introduction

Many civil engineering and mining applications involve the interaction of the natural ground with man-made structures and/or ground support systems. Different finite-element codes are capable of accounting for ground-support or soil-structure interaction (SSI) effects, by explicitly modeling the entire problem, i.e. ground and structure. Due to their complexity, simpler conventional design methods and codes often neglect SSI effects, and therefore may lead to results that can be inaccurate and may often be too conservative.

The concept of ground response curves (GRC) that allow for a graphical representation of the interaction of tunnel convergence with tunnel support was originally developed by the civil tunneling industry in order to facilitate the timing of support installation. GRC have the advantages of being both a relatively simple and efficient design tool, accounting for tunnel-support interaction when estimating stresses and deformations of both systems. The GRC approach is based on a series of simplifying assumptions (e.g. circular tunnel under a hydrostatic stress field, homogeneous ground, etc.) to avoid the complexities stemming from uneven loading at different points around the tunnel.

In this paper, two types of ground-support problems are discussed: room and pillar mines, and circular vertical shafts. The term ground-support used in this paper, in the case of the room-and-pillar mining, the room in between pillars represents the "ground", while the pillars are the "natural support". In the case of shafts, the excavation or cavity constitutes the "ground", while the liner is the "artificial support".

For both applications, the problem is simplified so that the interaction process of the ground and the support are fully accounted for, without the need for a full numerical analysis. This is achieved by deriving expressions for the spring stiffness equivalent to the ground boundary. Numerical models are then used for both derivation and verification of the proposed method.

2. Mine-pillar analogue to an elastic spring system

In the design of room-and-pillar systems, the loading capacity of a pillar and the assessment of pillar's factor of safety (FoS) have a significant economic impact, as they relate to the size of the opening and the extraction ratio. Pillar FoS is defined as the ultimate strength of the pillar divided by the stress acting on the pillar. The most generally accepted techniques for estimating pillar strength use empirical formulae based on survey data from actual mining conditions. Several different formulas for pillar strength can be found in the literature [1–4].

In contrast to pillar strength, little effort went into investigation of loading environment [5]. For initial analysis of the stresses acting on the pillar, the tributary area method is most commonly used

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[6]. This method simply assumes that the vertical gravitational pressure acting on half the span of the mine is imposed on the pillar. The pillar and mine act together to resist gravitational deformations. This interaction is not directly considered by the tributary area method. Moreover, due to the heterogeneous nature of the rock mass, the mine and pillar strength depends on both the intact rock properties and the shear strength of the natural discontinuities. The concentration of stresses directed from the mine to the pillar and the transient stresses induced upon the pillar through the excavation process likely cause the pillar strength to degrade due to progressive brittle damage in the form of crack growth and shearing of pre-existing joints. In turn, the weakening of the pillar influences the distribution of loads between the pillar and mine.

Oravecz developed an elastic analogue for determining stresses and displacements for pillars in coal mines, assuming that those were dictated by the compressibility of the seam [7]. The spring-analogue presented in this paper examines the mine-pillar interaction in terms of the deformation of the mine-pillar system and is not limited to the case of stratigraphic units and seams.

Esterhuizen et al. used the concept of ground response curves for presenting mine-pillar interaction [8]. In their work they used numerical analyses with the code FLAC (Itasca, [9]) to obtain pillar deformation results. The results were plotted in the form of mine-pillar interaction curves where the initial vertical pressure acting on the pillar was used as a reference point for plotting the vertical axis. In a similar context, Barczak et al. used numerical modeling to for ground response curves specifically developed for longwall tailgate standing support design [10].

The approach proposed in this paper is to develop simple equations that would obviate the need to build a full numerical model for pillar analysis. Elastic conditions are assumed, as it is argued that for elastic-brittle rock masses, where the peak elastic stress is followed by a rapid drop in material strength, an elastic analysis would be sufficient for estimating the ultimate pillar strength and pillar FoS. However, for deformable plastic rock mass the yielding will likely initiate simultaneously in both the mine and pillar, therefore it would be recommended to conduct fully elasto-plastic numerical analyses in order to obtain the characteristic curves for the mine and pillar loading system rather than to rely solely on the equations proposed in this paper.

2.1. Pillar spring analogue derivation

Given a rectangular excavation, (see Fig. 1), at a depth D below ground surface, and a rock material with unit weight, the vertical pre-mining pressure acting on the elevation of the excavated roof is:

$$P_O = \gamma \times D \tag{1}$$

The deformation of the mine-pillar system is affected by both the stiffness of the pillar, K_P, and the stiffness of the mine, K_M. In order to simplify the mine-pillar system to a spring system with a single degree of freedom, the distributed pressure P_O is substituted by an equivalent force, F_{EQ}. This is found by calculating the force that would yield the same maximum displacement Δ_M at the center of the roof of the mine system alone (i.e. assuming the absence of the pillar), as shown in Fig. 2.

For the given system, and assuming at this stage no high horizontal stresses are present (i.e. the horizontal-to-vertical stress ratio, k, is less than one), the equivalent force F_{EQ} can be approximated as:

$$F_{EQ} = 0.24L \times P_O \tag{2}$$

where L is the mine span. The mine span is equal to the width of the pillar plus the width of two rooms, and can be related to the extraction ratio, which is the ratio of extracted material to the total dimensions of the pillar and rooms.

The mine displacements are dependent and linearly proportional to the length of the unsupported span, the vertical pressure and the rock mass Young's modulus. The displacement occurs at both the roof and floor level of the mine; hence the mine convergence is twice the displacement Δ_M. Based on numerical modeling using the FEM code RS2 [11], and assuming a constant stress field, the mine displacement Δ_M is:

$$\Delta_M = \frac{L \times P_O}{E_M} \tag{3}$$

where L is the mine span and E_M is the rock mass Young's modulus of the mine. Note that the maximum displacement of the mine roof and floor Δ_M is calculated based on elastic analysis. The mine stiffness K_M is therefore:

$$K_M = \frac{F_{EQ}}{\Delta_M} = 0.24E_M \tag{4}$$

Eq. (4) shows that the mine stiffness is not dependent on the excavation geometry and is approximately one fourth of the rock mass deformation modulus.

The stiffness of the pillar K_P is a function of the rock mass Young's modulus of the pillar, E_P, the pillar height H and the pillar's cross section. In a plain strain analysis the pillar cross section is affected only by the pillar width, W. According to elastic theory, the stiffness of the pillar is:

$$K_P = E_P\frac{W}{H} \tag{5}$$

The idealization of the mine-pillar system to a discretized spring system is illustrated in Fig. 3. Initially, the system is converted into a system with two degrees of freedom, but owing to symmetry the problem can be further simplified and treated as a SDOF problem. Hence, f or the stiffness of the single spring the pillar height is taken as half the original height, and the stiffness is therefore doubled. As the mine-pillar system is represented by two parallel springs, the final deformation of the pillar is affected by the combined stiffness of the mine and the pillar, thus:

$$\Delta_P = F_{EQ}/(K_M + 2K_P) = 0.24L \times P_O \Big/ \left(0.24E_M + 2E_P\frac{W}{H}\right) \tag{6}$$

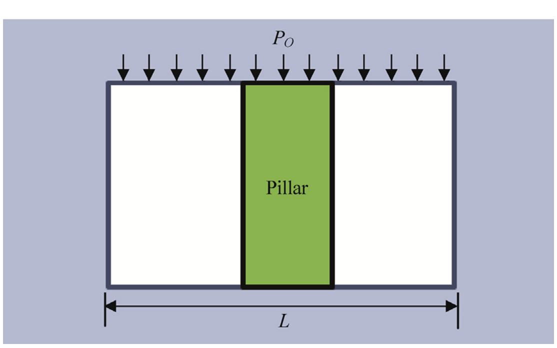

Fig. 1. Rectangular excavation with pillar at its center.

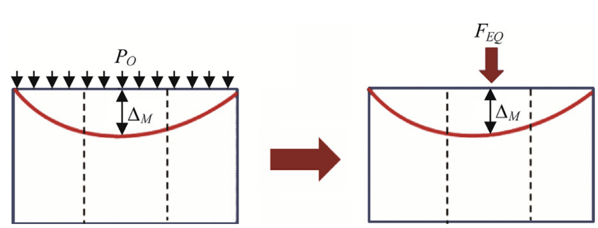

Fig. 2. Equivalent force F_{EQ}.