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A visco-elastic theoretical model for analysis of dynamic ground subsidence due to deep underground mining

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ABSTRACT

The dynamic ground subsidence due to mining is a complicated time-dependent process. Based on the theory of rock rheology, a theoretical model for the prediction and analysis of the dynamic subsidence due to deep underground mining is developed. The model is used for Chengjiao mine, an underground iron ore mine using pillarless sublevel caving method, to predict and analyse the subsidence in West and North mining areas. The theoretical results obtained were compared with actual subsidence data from West and North mining areas in Chengjiao Iron mine, eastern China. The agreement of the theoretical results with the filed measurements shows that the model is satisfactory and the formulae obtained are valid and thus can be effectively used for predicting the ground movement due to deep underground mining by pillarless sublevel caving method.

1. Introduction

Since the 1990s, there has been a growing demand for iron ore and steel products worldwide. With the development of world economy, the demand for mineral keeps increasing. However, shallow mineral resources are dwindling and iron mines in world have to get used to deep mining. Both observed and theoretical analysis show that the surface subsidence is continual and slow with a long duration of movement due to deep underground mining of iron deposits by the pillarless sublevel caving method.

As the result of the engineering development, the depth at which iron deposits are excavated has increased substantially reaching up to 1.2 km in China and 3 km in Canada. The underground mining at such great depths could induce geostress redistribution and rotation to the area surrounding mine workings. The change in geostress regimes (especially the high horizontal tectonic stress), in turn, leads to the large deformation for the occurrence of the rockmass displacement (surrounding rock failure), such as the stability of underground roadway, ground surface subsidence.

Many of mining practice proved that the range of overlying strata and ground surface movements (subsidence and deformation) have creep characteristics. It is the main factor of dynamic ground subsidence [1–10]. In addition, exploitation of minerals using caving methods such as the pillarless sublevel caving method will result in surface subsidence. For example, Chengjiao iron mine, in which the pillarless sublevel caving was used, there has been widespread deformation of land surface

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Nomenclature

P_z	in situ stress (MPa, kN/m^2)
γ	unit weight (kN/m^3)
H	mining depth (i.e. overburden thickness, m)
x	ground surface coordinate in horizontal direction (dependent on the coordinate system *xoz*)
t	time (year)
W_b (x, t)	subsidence of visco-elastic beam at point x at the moment t (m)
W_p (x, t)	subsidence of visco-elastic foundation at the point x at the moment t (m)
W (x, t)	dynamic ground subsidence due to underground deep mining (m)
W (0, t)	the roof deflection (subsidence) before filling in mining boundary (m)
U (x, t)	dynamic ground horizontal displacement due to deep mining (m)
σ	stress (MPa)
$\varepsilon(x, t)$	strain on the line parallel to the neutral axis (horizontal deformation of top layer of the beam (mm/m)
$\dot{\varepsilon} = \frac{\partial \varepsilon}{\partial t}$	rate of change of ε
z	distance from point x to the neutral axis (m)
$\rho(x, t)$	radius of curvature of the neutral axis (m)
E_b	elasticity modulus of the bending beam (GPa)
E_p	elastic modulus of the visco-elastic foundation (iron seam) (GPa)
E_k	elastic modulus of filling body (GPa)
η_b	viscosity coefficient of the bending beam (Pa s)
η_p	viscosity coefficient of visco-elastic foundation (Pa s)
η_k	viscosity coefficient of filling body (Pa s)
I	moment of inertia of cross-section (m^4)
A	the cross-section area of the beam (m^2)
$M(x, t)$	moment of cross section of the beam (kN m)
$q(x,t)$	external load of the rock beam (MPa)
$\varphi(x,t)$	foundation reaction force (MPa)
$\psi(x,t)$	reaction force of filling body for the visco-elastic beam (MPa)
m	mining thickness (m)
S	mining width of the sub-critical mining (m)
L	"half-wavelength" of stress wave and is a constant to be determined (m)
l	the width of gob (m)
W_{max}	maximum surface subsidence (m)
ξ	subsidence coefficient and is a constant to be determined (non-dimensional parameter)
L_0	mining width of the critical mining (m)
R	radius of influence of ground subsidence (m)
δ	the influence angle of ground subsidence (°)
v	rate of face advance (i.e. mining rate; m/year)

far away from the mining area. This phenomenon can cause environmental problems and damage to surface and subsurface structures. In order to protect the environment and structures from these damages, precise ground movement prediction is essential.

On the other hand, ground subsidence is a time dependent dynamic process. The development of ground movement, from the immediate roof to the surface, has a dynamic character and it is related to the progress of underground mining and time. In other words, ground surface subsidence due to deep mining is a dynamic process (time-dependent and rate-dependent) which obeys rock rheological principles. Ground movement prediction methods which can pre-calculate the final and intermediate stages of this process are important in mine design [1,3,4]. Deep rock masses show particular rheological properties, because of their complex geophysical environment and stress fields. Ground subsidence and deformation due to the underground deep mining, are complex processes affected by the mining method and velocity, timing of the mining process, rheological properties of overlying strata [6]. Therefore, it is necessary to study the dynamic ground subsidence due to deep mining.

In fact, ground movement is a major problem associated with deep underground mining of iron ore body, causing damage to subsurface structures and surface buildings. To avoid adverse impacts of ground subsidence, a reliable prediction is essential. The prediction and analysis of ground movement due to underground mining have been studied by many scholars in this field and valuable results have been obtained [1–36]. Many scientists from the UK, USA, China, Australia and other countries attempted to predict the ground subsidence of mines using numerous methods, such as the profile function methods [12–14,36], the influence function methods [15–20,36] and the void diffusion method [21]. Also, many theoretical studies are carried out using stochastic [22], elastic [23], and visco-elastic methods [6,8–10,24–26]. Recent efforts include the use of finite-element method [27,28], fuzzy system method [29], boundary element method [30], distinct element method [31],