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Prediction of cavern configurations from subsidence data

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ABSTRACT

An analytical method has been developed to predict the location, depth and size of caverns created at the interface between salt and overlying formations. A governing hyperbolic equation is used in a statistical analysis of the ground survey data to determine the cavern location, maximum subsidence, maximum surface slope and surface curvature under the sub-critical and critical conditions. The regression produces a set of subsidence components and a representative profile of the surface subsidence under sub-critical and critical conditions. Finite difference analyses using FLAC code correlate the subsidence components with the cavern size and depth under a variety of strengths and deformation moduli of the overburden. Empirical equations correlate the subsidence components with the cavern configurations and overburden properties. For the super-critical condition, a discrete element method (using UDEC code) is used to demonstrate the uncertainties of the ground movement and sinkhole development resulting from the complexity of the post-failure deformation and joint movements in the overburden.

1. Introduction

Salt and associated minerals in the Khorat and Sakon Nakhon basins, northeast of Thailand have become important resources for mineral exploitation and for use as host rock for product storage. For over four decades, local people have extracted the salt by using an old fashioned technique, called here the 'brine pumping' method. A shallow borehole is drilled into the rock unit directly above the salt. Brine (saline groundwater) is pumped through the borehole and left to evaporate on the ground surface. Relatively pure halite with slight amounts of associated soluble minerals is then obtained. This simple and low-cost method can, however, cause an environmental impact in the form of unpredictable ground subsidence, sinkholes and surface contamination (Fuenkajorn, 2002). Even though the brine pumping industry has been limited to strictly controlled areas, isolated from agricultural areas and farmlands, severe surface subsidence and sinkholes have commonly been found outside the controlled areas, particularly on the upstream side of the groundwater flow (Fig. 1).

The subsidence is caused by deformation or collapse of the cavern roof at the interface between the salt and overburden. Precise locations of the dissolved caverns are difficult to determine due to the complexity of groundwater circulation, infiltration of fresh surface water, brine pumping rates, and number and intensity of the pumping wells. As a result, location and magnitude of the subsidence are very unpredictable. Exploratory drilling and geophysical methods (e.g., resistivity and seismic surveys) have normally been employed to determine the size, depth and location of the underground cavities in the problem areas in an attempt to backfill the underground voids, hence minimizing the damage of the engineering structures and farmland on the surface (Wannakao et al., 2004; Jenkunawat, 2005, 2007). The geophysical and drilling investigations for such a widespread area are costly and time-consuming. This calls for a quick and low-cost method to determine the size, depth and location of the solution caverns. The method should be used as an early warning tool so that mitigation can be implemented before the uncontrollable and severe subsiding of the ground surface occurs.

The objective of this research is to develop a method to predict the location, depth and size of solution caverns created at the interface between the salt and the overlying formation. The effort includes statistical analysis of the ground survey data in the subsiding areas under sub-critical and critical conditions, numerical simulations to correlate subsidence components with the overburden properties, cavern diameter and depth, and formulation of empirical relations between the cavern configurations and the subsidence components.

2. Site conditions

Rock salt in the Maha Sarakham formation, northeast of Thailand is separated into 2 basins: the Sakon Nakhon basin and the Khorat basin. Both basins contain three distinct salt units: Upper, Middle and Lower members. Fig. 2 shows a typical stratigraphic section of the Maha Sarakham formation. The Sakon Nakhon basin in the north covers an area of approximately 17,000 km^2. The Khorat basin in the south covers more than 30,000 km^2 (Fig. 3). Warren (1999) gives a detailed description of the salt and geology of the basins. From over 300 exploratory boreholes drilled primarily for mineral exploration, Suwanich (1978) estimates the geologic reserve of the three salt members from both basins as 18 MM tons. Vattanasak (2006) has re-

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Fig. 1. Some sinkholes caused by brine pumping at Nonsabaeng village, Nongkwang, Banmuang district, Sakon Nakhon (Wannakao, 2004).

compiled the borehole data and proposes a preliminary design for salt solution mining caverns based on a series of finite element analyses, and suggests that the inferred reserve for solution mining of the Lower Salt member of the Khorat basin is about 20 billion tons. This estimate excludes residential and national forest areas.

Fig. 3 also shows the areas where the brine pumping has been practiced. Depths of the shallowest salt in those areas vary from 40 m to 200 m. It belongs to the Middle or Lower member, depending on locations. Most of the brine pumping practices are, however, in the areas where the topography is flat, groundwater table is near the surface, and the salt depth is less than 50 m in the Sakon Nakhon basin, and about 100 m in the Khorat basin (Wannakao et al., 2005; Jenkunawat, 2005). Based on field investigation, Jenkunawat (2007) states that the surface subsidence normally occurs in the areas where depth of the shallowest salt is less than 50 m. The overburden consists mainly of mudstone, siltstone, and sandstone of the Middle Clastic, and claystone and mudstone of the Lower Clastic, with fractures typically dipping less than 30°, and rarely at 70° (Crosby, 2007). The members are characterized by abundant halite and anhydrite-filled fractures and bands with typical thickness of 2 cm to 5 cm.

Direct shear tests performed as part of this research yield the cohesion and friction angle of 0.01 MPa and 33° for smooth saw-cut surfaces prepared from the Middle Clastic siltstone. The tests were performed under saturated condition. Fig. 4 shows the test results. More mechanical properties for these clastic members are summarized by Wannakao (2004) and Crosby (2007).

3. Statistical analysis of ground survey data

A statistical method is developed to determine the maximum subsidence magnitude, maximum slope profile, curvature of the ground surface, and the cavern location. The regression is performed on the ground survey data obtained from subsiding areas. It is assumed here that the cavern model is a half-oval shaped with the maximum diameter, w, located at the contact between the salt and the overburden. The ground surface, overburden and salt are horizontal. Fig. 5 identifies the variables used in this study. Since the cavern is assumed as half-oval shaped, the induced surface subsidence is axis symmetry. The radius of influence ($B/2$) represents the radius of the subsiding area where the vertical downward movement of the ground equals 1 cm or greater.

The survey data referred to here are the vertical displacements of the ground surface (z) measured at various points with respect to a global x–y coordinate (Fig. 6). A hyperbolic function modified from Singh (1992) is proposed to govern the characteristics of surface subsidence profile. It expresses the subsidence function, $S(r_i)$ (subsidence magnitude at point 'i', where i varied from 1 to the total number of measurements, n) as:

$$S(r_i) = a_0 \tanh(10a_1 r_i - a_2) + a_3 \qquad (i = 1, 2, 3 \ldots\ldots n) \tag{1}$$

where

$$r_i = \sqrt{(x_i - a_4)^2 + (y_i - a_5)^2} \tag{2}$$

r_i	distance from data point 'i' to the center of the group of data,
x_i, y_i	coordinates of subsidence measured at point 'i'

a_0, a_1, a_2, a_3, a_4 and a_5 are constants related to the subsidence components and coordinates of the maximum subsidence location, which can be defined as:

a_0	half of the maximum subsidence ($S_{\max}$),
a_1	scaling factor,
a_2	planar offset,
a_3	vertical offset,
a_4	$\Sigma x_i/n$, and
a_5	$\Sigma y_i/n$.

The above equation is modified from the hyperbolic function of Singh (1992) to allow a statistical analysis of field measurement data, and subsequently provides a smooth three-dimensional profile of surface subsidence for further analysis.

Similarly, the maximum slope (G) of the surface subsidence induced at the inflection point can be determined as:

$$G = S'(r_i) = 10a_0 \times a_1 \operatorname{sec}h^2(10a_1 r_i - a_2) \tag{3}$$

The maximum curvature (ρ) of the ground surface is calculated as:

$$\rho = S''(r_i) = -200a_0 a_1^2 \operatorname{sec}h^2(10a_1 r_i - a_2) \times \tanh(10a_1 r_i - a_2) \tag{4}$$

Regression analysis of the survey data using Eq. (1) will provide the three subsidence components and cavern location. These components will be correlated with the cavern depth and diameter in the following section. The regression also provides a smooth profile of the subsidence in three-dimension, as shown in Fig. 6. Accuracy of the results depends on the number, accuracy, and distribution of the field measurement points.

It is recognized that several theoretical models and governing equations have been developed to predict the subsiding characteristics