Design Guideline for Salt Solution Mining in Thailand

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Abstract

A general guideline has been developed for the design of salt solution-mined caverns in Sakon Nakorn and Khorat basins. Laboratory testing calibrates the mechanical and rheological properties of the salt formation. Via a series of numerical analyses, conservative configurations of the solution mine caverns are determined. It is recommended that the caverns be arranged in an array of single well system and should have the maximum diameter and height of 80 m and 60 m, respectively. The minimum spacing is estimated to be 240 m. The cavern field would yield an extraction ratio of 1.96 x 10^6 m^3 of rock salt per one square kilometer. The salt roof and floor should be greater than 200 m to prevent excessive movement of the cavern ground.

1. Introduction

The traditional (old) method of producing salt by pumping brine above the salt formations in Thailand has caused severe environmental impact. Such method can create shallow caves as the groundwater circulates, dissolves and removes the upper portion of the salt bed. Subsequently, a time-dependent subsidence of the upper formations and of the ground surface is unavoidable. In an extreme situation, uncontrollable sinkholes could be developed on the ground surface. Due to the complexity of the nature, prediction of the location, timing and magnitude of such ground movement and surface subsidence is not only difficult, but virtually impossible. The work described herein represents an attempt at promoting the method of salt solution mining by creating solution caverns at greater depth within the salt formation, while discouraging the method of brine pumping that has long been practiced. The development of solution mining caverns is rare in Thailand [1], as the solution mining technique is not widely known.

The objective of the present research is to derive a generic guideline for the design of solution caverns in rock salt formations in Thailand. The effort primarily involves compilation of the rock salt lithology in Khorat and Sakon Nakorn basins, laboratory mechanical testing, and computer modeling. Salt core specimens obtained from the Asia Pacific Potash Corp. have been subject to stress-rate controlled uniaxial tests, triaxial tests, and uniaxial creep tests to determine the strengths as well as the elastic and creep properties. The test results calibrate the rock model parameters in the computer simulations. A non-linear and time-dependent finite element code carries out the computation. Long-term mechanical stability and hydrological integrity of the salt caverns (up to 50 years) are of interest. This paper describes the design methodology and results.

2. Solution Mining Practices

Rock salt formations in Sakon Nakorn and Khorat basins are relatively thin and shallow as compared with those in the United States, Canada and Germany. The existing technology in those countries does not immediately applicable to our salt formations, as some procedural steps that have been used overseas may not be appropriate or conservative in term of mechanical stability of the cavern ground [2].

The single well system (an array of individual caverns) is thought to be appropriate

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for the relatively thin and shallow salt beds because the salt roof and inter-cavern pillars can provide mechanical support to the excavations [2]. This research therefore concentrates on the design of the single well system. Figure 1 shows a schematic layout of the single well method. In this system, a hole is drilled into the salt, cased and cemented back to the surface. A string of tubing is run inside the cemented casing into the salt. Dissolution is made by injecting fresh water into either the annulus of the casing or into the suspended tubing. When the fresh water is injected in the annulus and brine produced through the suspended tubing. This is called direct (forward) circulation. When the fresh water is injected in the hanging pipe and brine produced in the annulus. It is called reverse circulation.

A method has been developed to increase the shape control for the solution caverns [3]. It uses oil "blanket" placed at the top of the cavern to prevent the upper portion of salt from dissolving. Without the pad at the top, the lower density fresh water tends to dissolve along the roof. As the solution become more concentrated, it gains density and flows down the walls of the cavern. Figure 2a shows the shape of cavern that results from such process. Dissolution continues upward until the top of the salt is reached. This results in a large and unstable roof and leads to low recovery. Figure 2b shows the shape of cavern controlled by using oil blanket.

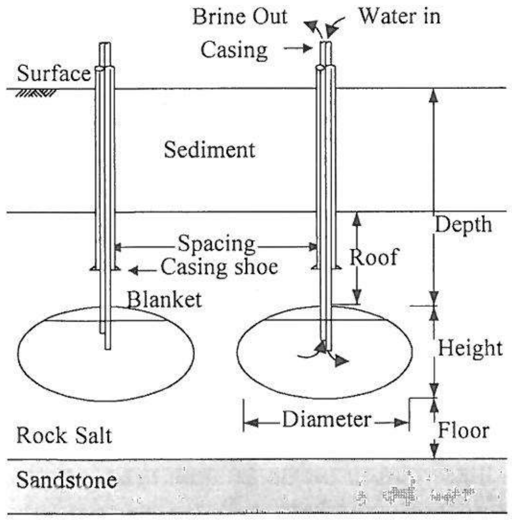

Figure 1 Design parameters for salt caverns.

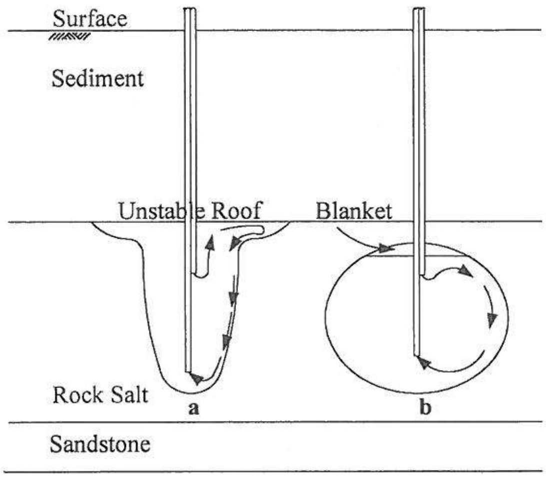

Figure 2 Effect of blanket on cavern shape (a) without pad (b) with pad.

The precise size and shape of the caverns are needed in the determination of mechanical stability. The method most commonly used in single well systems is called the sonar method. The tool takes sonar distance measurements at regular intervals through a 360 degrees rotation. It is raised or lowered to the next level and the process repeated. A three dimensional model of the cavern shape therefore can be constructed from the data.

3. Design Considerations and Process

In a broad scope, the design process and recommendations can be outlined as follows [3, 4].

(1) The need for production capacity is recognized either operationally or commercially.

(2) The initial scope should be identified, e.g., location, capacity, productivity, cost, etc.

(3) Conceptual design is derived, which involves finding locations, evaluating their suitability, preparing the technical data (maps, core-logging evaluation, design, cost estimates, etc.).

(4) A review by a commercial group to determine economic viability should be performed.

(5) The requirements for the project should be set out clearly and the information that is needed should be defined.

(6) The design strategy, principles and methodology should be drawn.

(7) The certain design should not duplicate the previous designs. A site-specific design must be developed.

4. Well Construction

4.1 Casing

Prior to mining the salt, a well (production hole) must be developed. In general the size of the final or production casing depends on the capacity desired for the well. All other casing is then sized to accommodate it. The numbers of other casings depend on the local requirements and subsurface conditions [3]. Typically, the diameter of the final cemented string is 20 cm and the diameter of the first casing is 40-50 cm. Characteristics and functions for each casing are described below from the outer most casing to the inner most casing.

Conductor Casing In many locations on the basins the first few meters of drilling are in unconsolidated sediments that are not self-supporting therefore an initial casing should be driven to the top of the first competent zone. This casing is called the conductor casing. Alternately, if the sediments stay open for a short time, the hole can be drilled to bedrock and casing set and cemented back to the surface.

Surface Casing The primary function is to protect or seal off any potable or fresh water aquifers. Cement is returned all the way back to the surface. Cementing is accomplished by injecting the cement into the casing, chasing it out the bottom and up the annulus with drilling mud.

Intermediate Casing If highly porous or fractured formations are encountered in the formations above the salt, an additional casing, called intermediate casing, may be required to isolate further drilling from these zones.

Production Casing If intermediate casing is set to seal off lost circulation, a second intermediate casing, called the production casing, should be set into the salt. In thin salt bed this casing is set 4-5 meters into the salt. In a very thick salt bed the casing can be set more than 30 meters into the salt. If the intermediate casing is successfully set into the salt, it becomes the production casing and further casing would be unnecessary. This casing is cemented to the surface.

Liner This casing is hung inside the production casing. It provides an annulus for access between casing and tubing. A liner can be used for intermediate injection or blanket control. Liners are not cemented.

Tubing One or two hanging tubes are the last casings hung in the well. These casings are the conduits used during dissolution for the injection and recovery of fluids. They are not cemented and are suspended from the well head. These suspended casings can be raised or lowered to control shape of the cavern.

4.2 Cavern Stability and Subsidence

Cavern stability and subsidence above solution mining operations has long been a source of concern and interest. Extensive researches have been conducted worldwide on predicting formation stability and measuring subsidence [5-7]. Several mathematical models for predicting subsidence have been proposed. Most use finite element analysis as the basic computational tool but vary in their approach to the mechanics of subsidence.

The formation of a sinkhole or crater is the final event associated with subsidence. It has been postulated that sinkhole may be formed by near-surface waters carrying sediments down through cracks and faults into the cavern. It is also possible that sinkhole results either from massive regional failure or relatively localized bulking into the cavern.

Subsidence monitoring above solution mining operations becomes necessary. It can be accomplished by precise leveling surveys similar to underground mine subsidence monitoring.

5. Rock Salt Sequences in Thailand

The sequences of rock salt that have been compiled by many investigators [8-11] are used here as data basis in selecting the site and analyzing the formation stability. They are from borehole logging data obtained as part of the potash exploration project in the northeast of Thailand. In this study, no attempt has been made at performing additional in-situ drilling or conducting any geological and geophysical exploration. It is assumed here that the pre-existing information is correct and reliable.

For an ease of modeling and design, the stratigraphic formations of salt and associated rocks have been conservatively reclassified here into five main geomechanics groups: (1) sediment, (2) mudstone and claystone, (3) anhydrite, (4) rock salt, and (5) sandstone and siltstone formations. The rock salt group represents the upper salt, middle salt, and lower salt beds, where available. The sandstone and siltstone group represents all rock formations below the salt formations. Figure 3 shows the stratigraphy of the five groups that have been reclassified based on the above criteria. The original designation numbers of the drilled holes are also given in the figure. The locations are referred to by using the name of the areas where the corresponding original drilled holes are located. Table 1 lists the names of the locations that represent these areas for both Sakorn Nakorn and Khorat basins. This does not mean that the areas that are not include in Table 1 are not suitable for the development of solution caverns. It is speculated that rock salt formations in several other locations on the Khorat plateau are feasible for solution mining. Only fourteen areas are selected as examples in this study because the drilled-hole information is available and their geology is favorable.

Table 1 Representative models and their locations.

Models	Locations
Nong Pule (Model NP)	(1) Ban Nong Plue, Borabue, Mahasarakham, K-089
Nong Kham (Model NK)	(1) Wat Pracha Nimit School, Ban Nong Kham, Bua Yai, Nakhon Ratchasima, K-075
Khok Sa-Nga (Model KS)	(1) Wat Tai Si Mongkhon, Muang, Yasothorn, K-011 (2) Wat Ban Du, Thawat Buri, Roi Et, K-015 (3) Ban Hua Khua, Kantharawichai, Mahasarakham, K-037 (4) Wat Suthimongkol, Pannanikom, Sakon Nakorn, K-043 (5) Ban Khok Sa-Nga, Phon, Khon Kaen, K-072
Po Phan (Model PP)	(1) Ban Khao, Muang, Udornthani, K-006 (2) Wat Nonwiake Srimuang, Wanorn Niwat, Sakon Nakorn, K-48 (3) Wat Umpawan, Ban Kudjig, Wanon Niwat, Sakon Nakorn, K-55 (4) Ban Po Phan, Na Chuak, Mahasarakham, K-87
Wat Kham (Model WK)	(1) Ban None Rawiang, Dan Khun thot, Nakhon Ratchasima, K-031 (2) Wat Kham, Kham Sakae Sang, Nakhon Ratchasima, K-077 (3) Ban Nong Prachak, Muang, Udon Thani, K-83

6. Cavern Design via Computer Modeling

For the past three decades several constitutive equations and creep laws have been developed to represent the rheological behavior of the salt. These laws have been implemented into numerical codes for use in explaining the mechanical and thermo-mechanical responses of rock salt under a variety of loading and boundary conditions [12-16]. A finite element code, called GEO [17-20] is selected in this study. It contains a rheological creep law describing the instantaneous and time-dependent behavior of rock salt under loading conditions. Figure 4 gives the modular system of the major (primary) behavioral components of GEO model showing the separation of the octahedral shear stress-strain relation from the mean stress-strain relation. They are independently analyzed because they produce mutually opposing effects: the shear stress-strain relation represents a destructive mechanism, while the mean stress-strain relation represents a strengthening mechanism. The model simultaneously describes the shear behavior (by a linear sum of the elastic, viscoelastic, and viscoplastic strain components) and the mean behavior (by a linear sum of the elastic, viscoelastic, volumetric expansion [dilation], and thermal expansion strains).

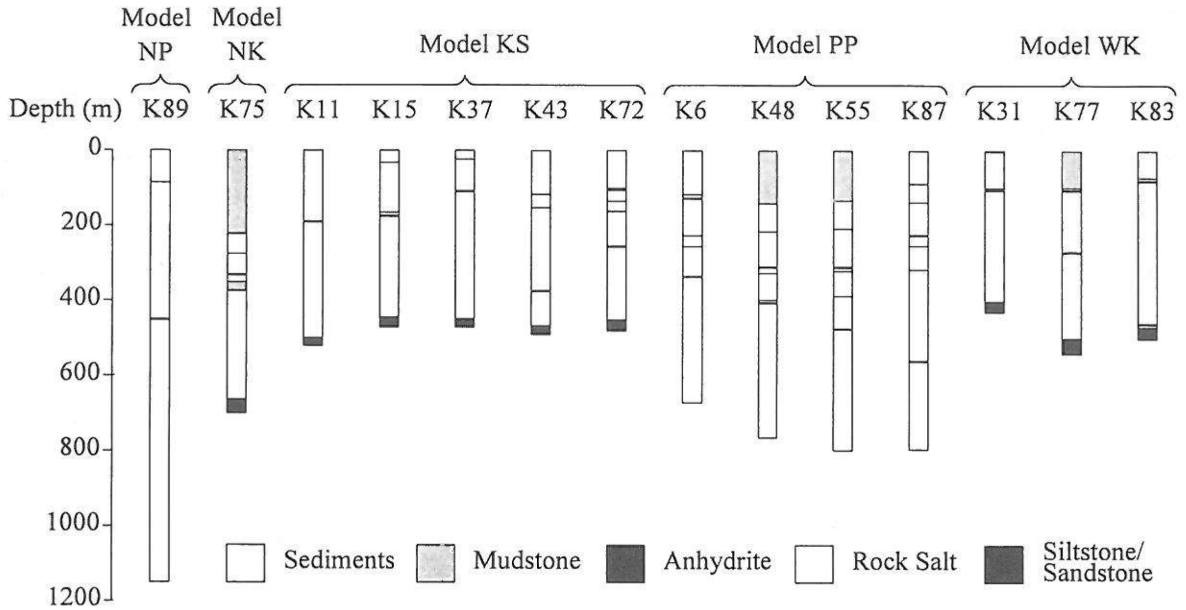

Figure 3 Geomechanics classification of salt sequences and associated rocks.

Table 2 Properties of rock salt and associated rocks.

Properties	Units	Sediment	Mudstone	Anhydrite	Salt	Siltstone/ Sandstone
Shear Modulus, G_1	10^9 Pa	0.034	0.345	3.448	5.931	13.793
Retarded Shear Modulus (τ_0<K_0), G_2	10^9 Pa	0.069	0.345	13.793	9.655	13.793
Elastoviscosity (τ_0<K_0), V_2	10^9 Pa·day	0.007	0.034	3.448	0.172	3.448
Plastoviscosity, V_4	10^9 Pa·day	2.759	2.759	27.586	2.276	13.793
Ultimate Bulk Modulus, K_1	10^9 Pa	0.069	1.724	82.759	27.586	82.759
Unconfined Octah. Shear Strength	10^3 Pa	0.069	0.345	0.690	0.345	0.690
Ultimate Octah. Shear Strength, K_0	10^3 Pa	0.690	3.448	6.897	3.448	6.897
Critical Strain of Failure	-	0.010	0.010	0.010	0.010	0.002
Density Gradient	10^6 Pa/m	-0.025	-0.025	-0.025	-0.021	-0.025

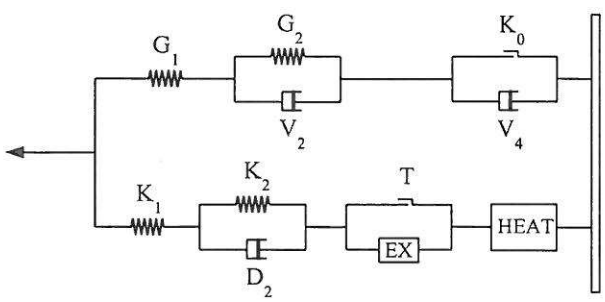

Figure 4 Modular representation of constitutive equation for geological materials, including rock salt.

Computer modeling has been performed here to assess the mechanical performance of rock salt around the brine cavern under isothermal condition. The finite element code GEO carries out the computation under explicit time domain, and hence it is capable of predicting the stress and deformation of the surrounding salt and of the overlying formations through the next 50 years.

The rock strength, elastic, visco-elastic and visco-plastic property parameters are determined by means of statistical analysis on the results of uniaxial creep tests, stress-rate-controlled uniaxial tests and triaxial tests. Table 2 lists property parameters of the five geomechanics groups. The salt properties are comparable to those obtained from the salts elsewhere [21]. For the properties of the sediment, claystone, mudstone, anhydrite and siltstone/sandstone formations, the information from the GEO database is used. Conservative approach has been taken in the assignment of the parameters in these groups.

Finite element meshes have been constructed for the five representative areas. The analysis is made in plane strain. The cavern ground is discretized from the ground surface to the depth below the salt formations. The initial in-situ stress is assumed to be hydrostatic. The vertical stress at any point in the model is calcualted from the depth and density of the overburden. The cavern internal pressure is equal to the hydrostatic pressure of saturated brine.

GEO computes the distribution of the stresses and strains in the rock around the caverns from the first day after cavern development through the next 50 years. All caverns arranged in the square grid array are mined simultaneously. After several trial simulations and from the previous related studies, the cavern size and shape have been pre-determined in the models. The determination is based on the criteria that the cavern capacity (salt productivity) is maximized while maintaining the long-term mechanical stability. The results from the simulations are analyzed and compared in terms of the stress, strain, closure and surface subsidence. Different representative models yield different behavior of the cavern ground, and hence lead to the difference in the recommended cavern depths. Figures 5 and 6 compares the horizontal and vertical closure of the caverns from the five models. The maximum closure is less than 20 centimeters. Figure 7 compares the predicted surface subsidence for the five models through the next 50 years. The maximum ground surface subsidence is about 10 centimeters. Table 3 summarizes the design recommendations. With these design parameters (spacing, diameter, etc.), the extraction of the rock salt is about 1.96×10^6 m^3 for one square kilometer of the mined area.

Care should be taken in applying the design results offered in this paper. Even though several conservative approaches have been taken throughout the investigation, intrinsic variability of the rocks and non-uniform distribution of the formations have not been explicitly incorporated. The analysis also assumes that the properties of salt in both basins can be represented by the ones obtained in this research. Site-specific data may be needed to ensure that the design recommendations are truly applicable in other different locations that are not included here.

7. Conclusions

The objective of the research is to derive a general guideline for the design of solution caverns in rock salt formations in Thailand. The effort primarily involves compilation of the rock salt lithology in Khorat and Sakon Nakorn basins, laboratory mechanical testing, and computer modeling. Salt core specimens obtained from the Asia Pacific Potash Corp. have been subject to stress-rate controlled uniaxial tests, uniaxial

Table 3 Design recommendations.

Model	Diameter (m)	Height (m)	Depth (m)	Salt Roof (m)	Spacing (m)
KS	80	60	315	212	240
NK	80	60	525	249	240
NP	80	60	942	856	240
PP	80	60	589	380	240
WK	80	60	301	204	240

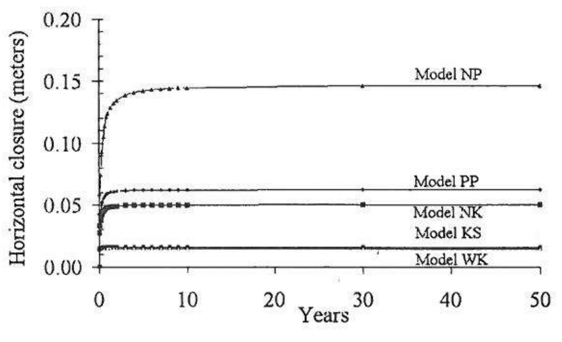

Figure 5 Horizontal closure of cavern models.

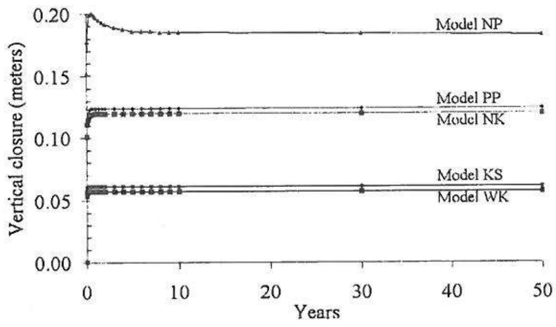

Figure 6 Vertical closure of cavern models.

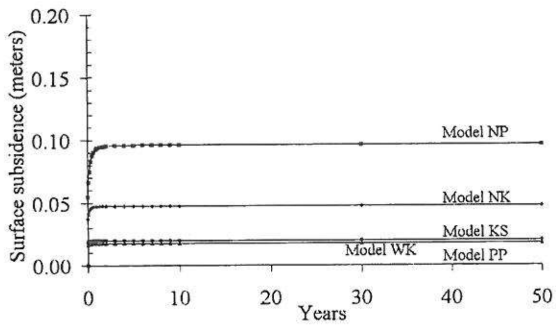

Figure 7 Surface subsidence.

creep tests and triaxial compression tests to determine the strengths as well as the elastic and creep properties. The test results calibrate the rock model parameters in the computer simulation. A non-linear and time-dependent finite element code GEO carries out the computation. Long-term mechanical stability and hydrological integrity of the salt caverns are of interest. The design is aimed at maximizing the extraction ratio while minimizing the surface subsidence.

For an array of single well system, the cavern in these groups should have the maximum diameter and height of 80 m and 60 m, respectively. The minimum spacing (center-to-center) should be 240 m. Under these optimized parameters the cavern field would yield an extraction ratio of 1.96×10^6 m^3 of rock salt per one square kilometer. The cavern should be mined in the middle of the salt bed. The salt roof and floor should be greater than 200 m.

8. Acknowledgments

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