Rock Salt Formations as Potential Nuclear Waste Repository

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Abstract

A series of laboratory testing and numerical simulations have been carried out to assess the mechanical performance of the rock salt formations for the potential nuclear waste disposal in Thailand. Uniaxial creep tests and stress-controlled tests determine the mechanical and rheological properties (strength, elastic, visco-elastic and visco-plastic parameters) of rock salt specimens obtained from Udon Thani. Based on the existing borehole information, five geologically favorable areas in Sakon Nakorn and Khorat basins are assumed as tentative repository sites. The computer modeling uses the laboratory-calibrated properties to simulate the time-dependent stress, strain and deformation around the salt cavern, as well as the movement of the overlying formations. The design emphasizes the mechanical stability under isothermal conditions during the waste emplacement (currently aimed at 50 years), and the long-term isolation for the next 500 years. The preliminary results from the area of Ban Kudjig, Wanon Niwat district, Sakon Nakorn province (one of the selected areas) suggest that long-term stability of the disposed caverns may be achieved if suitable design configurations have been implemented. The caverns should be solution-mined below 585 meters depth. The maximum diameter of the spherical shaped cavern should be 40 meters (equivalent to 25,133 m^3). The minimum salt roof and floor are 200 meters. The surface subsidence is calculated to be less than one cm through the next 500 years, providing that the internal pressure is maintained to be equivalent to the hydrostatic pressure of saturated brine.

1. Introduction

The increasing amount of nuclear wastes in Thailand has called for a permanent solution to dispose of or isolate these harmful materials from the biosphere. The low level wastes, collected from the hospitals, laboratories, and the Office of Atomic Energy for Peace (OAEP), may require the isolation period as long as 500 years, or at least until the radionuclide reaches an acceptable level. A common solution to this problem that has been practiced internationally is to dispose such wastes into the geologic media [1-6]. The method invokes the characteristics of the host rock and the properties of engineering barriers to ensure the long-term isolation [7]. Several types of geologic formations have been under consideration for the host rock, e.g. tuff, basalt, granite and salt. In the U.S. and Germany, rock salt has long been one of the prime candidates, primarily due to its mechanical stability, low permeability, healing capability, and availability [8, 9]. Extensive research on rock salt has been carried out in the North America and Europe for the past 30 years. Much effort has been aimed at determining the mechanical, thermo-mechanical, chemical and hydrological properties and behavior of the rock [10-13]. Even though extensive rock salt formations in the northern part of Thailand exist, the necessary information regarding their mechanical performance and hydrological integrity is not available.

The objective of the present research is to assess experimentally and numerically the mechanical performance of the salt formations for use as nuclear waste repository in Thailand. The work serves as a mission of the OAEP in an attempt at minimizing the environmental impact from the wastes by isolating them permanently from the biosphere. The research effort primarily involves compilation of available data on the salt sequences, mechanical laboratory testing, and computer simulations for the preliminary design. Described herein are the methodology and results of the study.

It should be recognized that this study only concentrates on the mechanical performance assessment of the rock salt under some aspects of the repository environments. Even though there are numerous factors needed to be considered for the geologic disposal, they are beyond the scope of this study. It is suggested that unless the geomechanical stability of the repository salt can be ensured, geologic disposal would not be possible [5, 6, 14, 15]. The proposed repository locations defined here are tentative. The official repository sites have not been determined.

2. Rock Salt Formations in Northeast Thailand

The sequences of rock salt in Thailand that have been compiled by many investigators [16-21] are used here as data basis in selecting the site and analyzing the formation stability. They are obtained from borehole logging conducted as part of the potash exploration project in the northeast Thailand. For this preliminary 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 reclassified here into three main geomechanics groups: (1) associated rocks, (2) rock salt, and (3) sandstone and siltstone formations. The associated rocks include all geological formations between and above the salt formations (e.g., anhydrite, mudstone, clay, claystone, siltstone, conglomerate, terrain sediment, alluvial deposits, etc.). The rock salt group represents the upper salt, middle salt, and lower salt beds. The sandstone and siltstone group represents all rock formations below the salt formations.

One of the difficulties in selecting a suitable repository site is that the salt formations in Thailand are relatively thin and shallow, as compared with those in the U.S. and Germany. The selection criteria used here are that the thickness and depth of the rock salt group must be as great as possible, and that the inter-beds between them should be insignificant. Based on these criteria and from the available information from the drilled holes, five areas on the Khorat plateau have been taken into consideration. Figure 1 shows the stratigraphy of the five areas 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 using the name of the areas where the corresponding original drilled holes are located. Table 1 lists the names of these locations for both Sakorn Nakorn and Khorat basins.

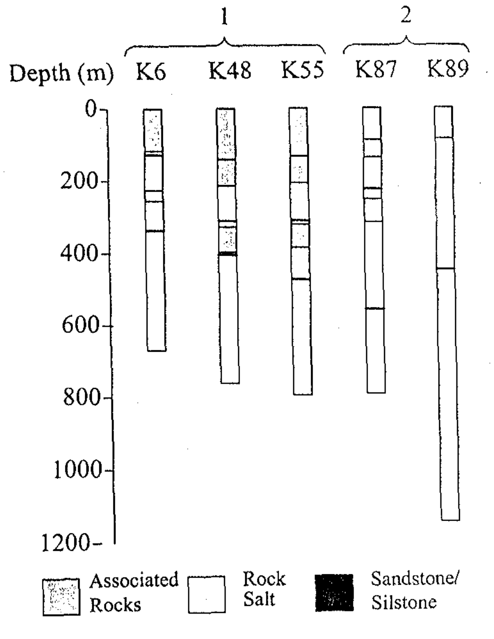

Figure 1 Stratigraphy of salt and associated rocks in Sakon Nakorn (1) and Khorat (2) basins, after re-classification into geomechanics

3. Mechanical Laboratory Testing

Salt cores have been obtained from the Asia Pacific Potash Corporation, Ltd. in Udon Thani province. They have been drilled from the middle and lower salt beds at depth ranging between 250 m and 400 m. The nominal diameter of the cores is 152 mm. They have been cut to appropriate length for the uniaxial creep testing and stress-rate-controlled uniaxial testing. Sample preparation and test procedure follow the applicable ASTM standards [22, 23], as much as practical. Thirteen uniaxial test specimens have been loaded to failure under constant rates ranging from 0.01 MPa/s to 1.0 MPa/s. The immediate objective of this test is to assess the time-dependent effect on the compressive strength of the salt. Table 2 summarizes the results. Figures 2 through 5 plot the axial stress as a function of axial strain. The axial strain at which the failure occurs tends to increase as the loading rate decreases. The mathematical relationship between the strength and the loading rate remains inconclusive. This is probably due to the high intrinsic variability of the salt. The uniaxial creep test has been performed on six salt specimens under the constant axial stresses between 10 to 30 MPa. For this test series, the specimens are loaded axially until failure or until the test duration reaches seven hours. Figure 6 shows the axial strain-time curves for some specimens. Instantaneous, transient and steady-state strains are observed in alll specimens. For the specimen subjected to the constant axial stress of 30 MPa, tertiary creep phase is detected prior to failure. In general the creep behavior and strength results agree well with those reported elsewhere [24, 25].

Table 1 Tentative areas in Sakon Nakorn and Khorat basins assumed in this study.

Basin	Locations
1. Sakon Nakorn	1) Ban Khao, Muang, Udornthani, K-006 2) Wat Nonwiake Srimuang, Wanorn Niwat, Sakon Nakorn, K-048 3) Wat Umpawan, Ban Kudjig, Wanon Niwat, Sakon Nakorn, K-055
2. Khorat	1) Ban Po Phan, Na Chuak, Mahasarakham, K-087 2) Ban Nong Plue, Borabue, Mahasarakham, K-089

4. Theoretical Derivation of GEO Program

The rheological constitutive model used here is capable of simulating the elastic, visco-elastic, visco-plastic, strain softening and dilation behavior of time-dependent materials, such as rock salt. The detailed formulation and algorithm of the constitutive equations are described elsewhere [26-29], and hence

Table 2 Results of stress-rate-controlled uniaxial testing.

Samples	Average diameter D (mm)	Average length L (mm)	Depth (m)	Compressive strength σ_c (MPa)
UN01	61.18	150.53	257.90	24.22
UN02	60.62	151.94	384.30	35.26
UN03	61.35	154.00	392.95	25.88
UN04	58.73	154.23	390.55	37.61
UN05	61.32	152.85	390.72	28.82
UN06	60.78	150.25	391.37	31.52
UN07	60.52	154.78	392.80	20.34
UN08	60.90	148.25	391.77	39.27
UN09	60.99	155.18	258.05	18.89
UN10	60.78	148.89	252.05	19.78
UN11	61.10	156.17	252.45	10.96
UN12	60.94	148.65	391.57	34.14
UN13	61.10	156.17	253.00	29.10
Average compressive strength				27.37 ± 2.32

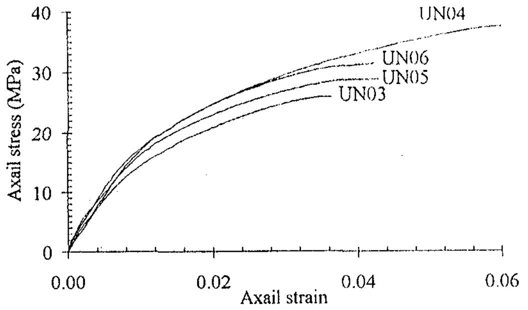

Figure 2 Uniaxial compressive strengths Under loading rates of 0.01 and 0.05 MPa/s.

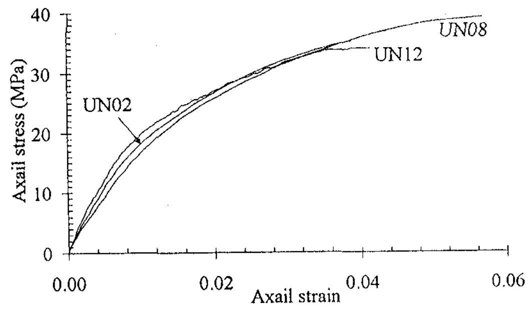

Figure 3 Uniaxial compressive strengths under loading rate of 0.1 MPa/s.

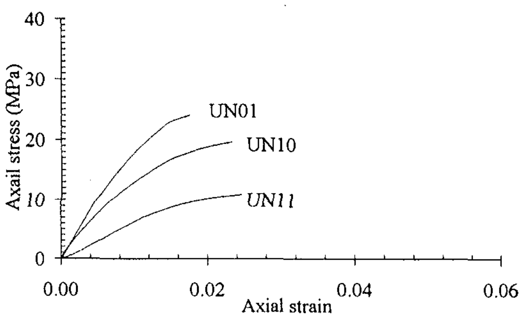

Figure 4 Uniaxial compressive strengths under loading rate of 0.5 MPa/s.

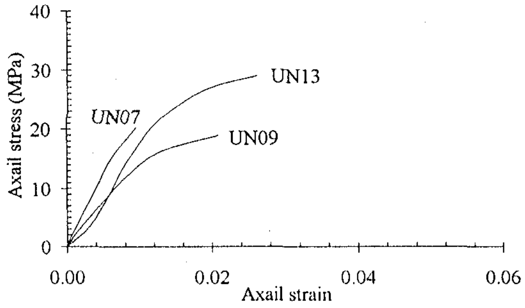

Figure 5 Uniaxial compressive strengths under loading rate of 1.0 MPa/s.

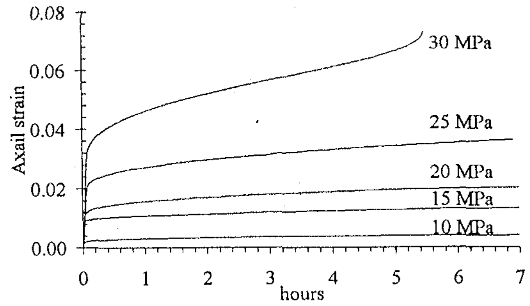

Figure 6 Uniaxial creep test results.

are not repeated here. These equations have been incorporated into a finite element code, named GEO. A brief discussion identifying its unique derivation of the constitutive equations is given below.

The von Mises criterion is used to describe the failure surface and to develop a strain-softening model for geologic materials. It is proposed that the octahedral shear strength K_O increases with an increase of the mean stress σ_m. The relation can be expressed as:

$$\partial K_O/\partial\sigma_m = \alpha(K^B - K_O), \qquad (1)$$

where α is a yield surface coefficient, and K^B is an ultimate octahedral shear strength. Equation (1) leads to the following expression of a compressive failure criterion, which is applicable for brittle to ductile materials:

$$K_O = K^A + (K^B - K^A)\,[1 - \exp(-\alpha\sigma_m)], \tag{2}$$

where K^A is an unconfined octahedral shear strength. During strain-softening, the strength of rock decreases or deteriorates. The ultimate deterioration of the material is defined as the state at which the inter-crystalline cohesive bonds are completely lost, as in a mass of loose sand. The strength K_O in this state then becomes the residual strength K_R, which reflects the internal friction strength in the pulverized mass, given by the function of confinement σ_m:

$$K^R = K^B\,\sigma_m/P, \tag{3}$$

where K^B/P is friction tangent ($\tan\theta$), P is the plastic transition pressure, and θ is the angle of internal friction. Rock deterioration progresses from the intact to the residual strength (K_O to K^R) with an increase in the excess octahedral shear strain $\Delta\gamma_O$. The K_O of the deteriorated rock can be determined by adding the residual strength K^R to the variable portion ΔK_O, which varies from 0 to 100%, depending on the amount of the deterioration. Thus the strength can be defined as:

$$K_O = f_D\,\Delta K_O + K^R, \tag{4}$$

where f_D is the deteriorating function and ΔK_O is the variance portion of the strength which equals $[K^A + (K^B - K^A)\,(1 - \exp\,(-\alpha\sigma_m)] - K^R$. f_D can be related to the excess octahedral shear strain as:

$$f_D = \exp\,[-C(\gamma_O - \gamma_C)/\gamma_C];\ \gamma_O > \gamma_C, \tag{5}$$

where C is a deterioration coefficient, γ_C is a critical strain of elastic limit, and γ_O is the induced octahedral shear strain. By introducing equation (5) into equation (4), the strength deterioration function describing the strain-softening behavior of rock after γ_O exceeds γ_C, can be established:

$$K_O = \exp[-C(\gamma_O - \gamma_C)/\gamma_C]\ \{[K^A + (K^B - K^A)\,(1 - \exp(-\alpha\sigma_m))] - K^B\sigma_m/P\} + K^B\,\sigma_m/P, \tag{6}$$

Laboratory observations made by various investigators show that the non-recoverable volumetric dilation ε_{VD} starts to increase immediately after micro-cracks are initiated. It is postulated that the dilation progressively increases with increases of the excess shear strain (γ_O - γ_C). This may be expressed in an exponential form as:

$$\varepsilon_{VD} = F\{\exp[C(\gamma_O - \gamma_C)/\,\gamma_C] - 1\};\ \gamma_O > \gamma_C, \tag{7}$$

where F is dilation coefficient. The ε_{VD} value decreases with an increase of plasticity or mean stress σ_m because this non-recoverable dilation is caused by the brittle failure. In the plastic state, with the mean stress larger than the plastic transition pressure P, there will be no dilation. The brittle effect f_B due to the deficient mean stress can be defined by:

$$f_B = \exp\,[-H\,\sigma_m/(P - \sigma_m)];\ \sigma_m < P, \tag{8}$$

where P is the minimum σ_m required for the strongest crystals of the grain to yield plastically, and H is a confinement coefficient. In equation (8), f_B varies from 1 toward 0 for σ_m increasing from O toward P. The volumetric dilation function can be formulated by multiplying equation (7) by (8):

$$\varepsilon_{VD} = F\{\exp[C(\gamma_O - \gamma_C)/\,\gamma_C] - 1\};\ \exp[-H\sigma_m/(P - \sigma_m)];\quad \gamma_O > \gamma_C \text{ and } \sigma_m < P, \tag{9}$$

The strength deterioration and volumetric dilation functions, equations (6) and (9) have been incorporated into a nonlinear time-dependent finite element code GEO. Based on the infinitesimal strain theory, the code employs four-noded isoparametric quadrilateral elements to compute displacements, stresses and strains for isotropic materials. The built-in constitutive equations are derived for elastic, visco-elastic and visco-plastic analyses. The constitutive differential equations and finite element formulation for these rheological analyses can be seen elsewhere, and hence will not be repeated here.

Figure 7 shows the incorporation of K_O (represented by the Bingham element) and dilation (EX) functions into the behavioral system of GEO model. The formulation separates the octahedral shear stress-strain (σ_m - ε_m) relation. These relations act in parallel and are related via failure and post-failure conditions (i.e. deterioration coefficient C). The program carries out the explicit time-domain integration, and hence allows updating the element strength and state (elastic or plastic) through different time steps. The formulation is designed such that when the induced shear strain (γ_O) is less than the critical shear strain (γ_C), element behaves as an elastic or visco-elastic, and does not dilate. Immediately after γ_O exceeds γ_C and σ_m us less than P, K_O decreases, and results in a strain-softening behavior. Under this condition, the calculation for a new failure surface and volumetric dilation will be carried out for that particular element. The new K_O is then returned to the main algorithm to compare with the current stress state. The calculated ε_{VD} is added to the elastic and plastic strain components in the minimum principal stress direction.

Under large confinements (σ_m > P), the strength will not deteriorate, and dilation will not occur (ε_{VD} = 0). The element may deform in strain hardening mode or may flow plastically, depending on the amount of γ_O.

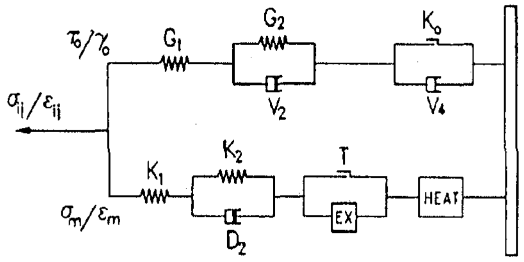

Figure 7 GEO rheological components.

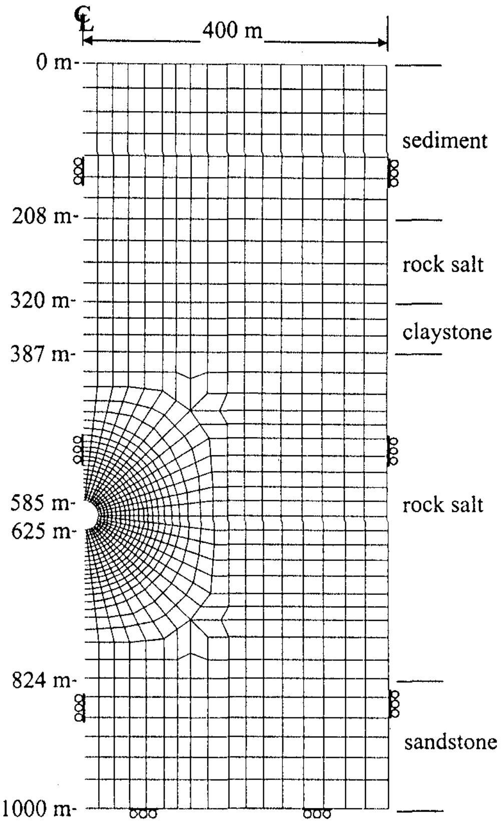

Figure 8 Finite element model for disposal cavern at Ban Kudjig, Sakon Nakorn province.

5. Computer Simulations

The experimental results are used to calibrate the strength, elastic and time-dependent parameters in the GEO program. Regression analyses are performed on the stress-strain curves and on the strain-time curves. Table 3 lists these parameters. For the properties of the sediment, claystone and siltstone/sandstone formations, we use the information from the GEO database because their specimens are not available for testing. The existing mechanical properties on such formations have not been published. Conservative approach has been taken in the assignment of each parameter.

One of the conceptual designs for underground disposal in rock salt invokes the solution mining technology [4]. Salt excavation by mean of dissolution would make the project economically favorable. The method also minimizes the geologic penetrations to the disposed wastes, and hence minimizes the sealing effort. At this preliminary state, spherical shaped cavern is assumed. For each cavern the capacity is designed as 20,000 m^3, defined by the amount of the wastes produced in Thailand for the next 50 years. It is conservatively assumed that only one-tenth of the cavern capacity is allowed before sealing. Since the disposed materials are primarily the low-level wastes, a constant room temperature (25-27°C) is taken throughout the modeling and experiment.

In this paper the computer modeling at Ban Kudjig, Wanon Niwat, Sakon Nakorn province is described. A finite element model (mesh) is constructed to represent a vertical cross-section of the cavern ground (Figure 8). It is assumed that the disposal cavern is single and isolated in a large mass of geologic media. No nearby excavation exists. The cavern diameter is 40 m (equivalent to 25,133 m^3). The rock formations are discretized from the ground surface to the depth of 1000 m. The model covers a horizontal (radial) distance of 400 m. The left boundary is the cavern axis. The right boundary is defined to be 10 times the cavern diameter. In order to show the cavern boundaries, the elements inside the cavern are not drawn in the figure. Small elements are used adjacent and near the cavern boundaries to capture the detailed distribution of the stresses and strains under high gradients. Larger elements are used in the overburden (far from the cavern roof) because its behavior does not impact the cavern

Table 3 Properties of rock salt and associated rocks.

Properties	Units	Associated Rocks	Rock Salt	Sandstone/ Siltstone
Shear Modulus	10^9 Pa	0.345	5.931	13.793
Retarded Shear Modulus ($\tau_0 < K_0$)	10^9 Pa	0.345	9.655	13.793
Elastoviscosity ($\tau_0 < K_0$)	10^9 Pa·day	0.345	0.172	3.448
Plastoviscosity	10^9 Pa·day	2.759	2.276	13.793
Ultimate Bulk Modulus	10^9 Pa	1.724	27.586	82.759
Unconfined Octah. Shear Strength	10^3 Pa	0.069	0.379	0.690
Ultimate Octah. Shear Strength	10^3 Pa	0.690	3.793	6.897
Critical Strain of Failure	-	0.010	0.002	0.002
Density Gradient	10^6 Pa/m	-0.025	-0.021	-0.025

stability. The overburden is included to provide the gravitational weight on the salt cavern, and to allow an assessment of the ground surface subsidence.

The analysis is made in axisymetric. The stress field at the site is assumed to be hydrostatic. The vertical stress at any point in the model is computed from the depth and density of the overburden. The internal pressure of the cavern equals the hydrostatic pressure of saturated brine. It is assumed to be constant during the emplacement and through the isolation period.

GEO computes the stress, strain and deformation of the cavern ground from the frist day after cavern development through the next 500 years. The results suggest that the time-dependent strain will be induced in salt adjacent to the cavern wall. This results in the closure of the cavern up to 10 cm. The ground surface subsidence occurs within the first year after excavation and remains constant at about 1 cm through the next 500 years. Analyses of the stress and strain distributions imply that the surrounding salt remains mechanically stable (Figures 9 and 10). This is probably due to the fact that the cavern shape is highly favorable (small spherical shape), and that it is mined within a relatively thick salt mass while maintaining the internal pressure of approximately half the in-situ stresses.

6. Discussions

It is well recognized that geologic disposal involves a variety of extensive, well-planned and rigorous investigations. Some of which includes environmental impact, geological suitability, mechanical stability, hydrologic influence, climate changes, radiation effects, land-use, existing regulations, and social and political impacts, etc. The present research only assesses the mechanical performance under the repository environment. The investigation is based on several strong assumptions due to the fact that the needed information and the influence from other factors remain largely unknown. Nevertheless, long-term stability and containment integrity remains a crucial issue. Unless the geomechanical stability of the cavern ground can be ensured, the salt repository would not be possible.

Selection of the areas that are geologically suitable is not trivial. This is primarily due to the lack of necessary subsurface information. Most existing exploratory holes have been concentrated in small areas. As a result, geological correlation of the salt and its associated rocks for the entire Khorat plateau is relatively crude. Depth and thickness of these formations in most areas remain uncertain.

Due to the uncertainties and limitations of the data, care should be taken in applying the design results offerred in this paper. Even though conservative approaches have been taken, intrinsic variability of the rocks and non-uniform distribution of the formations have not been explicitly incorporated. Additional mechanical and geological data are needed to ensure that the model truly represents the actual in-situ conditions.

On the aspect of the mechanical performance in this research, the future work will include a series of triaxial creep testing and triaxial compressive strength testing. The salt properties will be further refined to obtain a more representative set of parameters. An attempt will also be made at determining the mechanical properties of the associated rocks. A conceptual design using the dry mining technology will be analyzed for the potential repository.

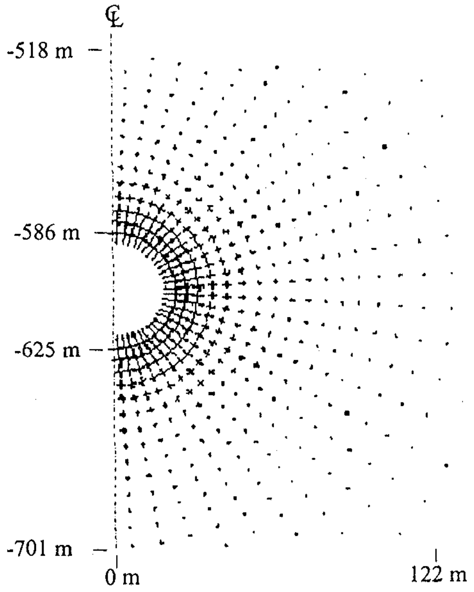

Figure 9 Principal strain vectors around cavern at 500 years after emplacement.

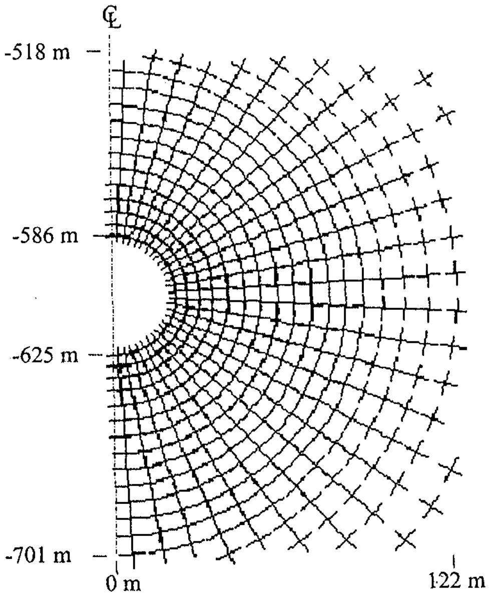

Figure 10 Principal stress vectors around cavern at 500 years after emplacement.

7. Conclusions

Computer modeling has been performed to assess the mechanical performance of rock salt around the repository cavern under isothermal condition. The rock strength, elastic, visco-elastic and visco-plastic property parameters are determined by means of regression analysis on the results of uniaxial creep tests and stress-rate-controlled uniaxial tests. A 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 500 years. Five geologically favorable areas have been selected based on the existing borehole information obtained from the Khorat plateau. The design invokes the concept of solution mines as applied to the repository cavern. It is assumed that the salt properties are representative of both Sakon Nakorn and Khorat basins, and that the existing information on the salt sequences is correct and remains unchanged through the isolation period. Under these simplified boundary and loading conditions, it may be mechanically feasible that the salt formations are used as repository rock. The preliminary results from the area of Ban Kudjig, Wanon Niwat district, Sakon Nakorn province (one of the selected areas) suggest that a long-term stability of the disposed caverns may be achieved if suitable design configurations have been implemented. The caverns should be solution-mined below 585 meters depth. The maximum diameter of the spherical shaped cavern should be 40 meters (equivalent to 25,133 m^3). The minimum salt roof and floor are 200 meters. The surface subsidence is calculated to be less than one cm through the next 500 years, providing that the internal pressure is maintained to be equivalent to the hydrostatic pressure of saturated brine.

8. Nomenclature

α = Yield surface coefficient
γ_C = Critical octahedral shear strain
γ_O = Octahedral shear strain
ε_m = Mean strain
ε_{VC} = Volumetric dilation
σ_C = Uniaxial compressive strength
σ_m = Mean stress
C = Deterioration coefficient
D = Average diameter of salt specimen
f_B = Brittle effect
f_D = Deteriorating function
H = Confinement coefficient
K^A = Unconfined octahedral shear strength
K^B = Ultimate octahedral shear strength
K^R = Residual octahedral shear strength
K_O = Octahedral shear strength
L = Average length of salt specimen
P = Plastic transition pressure

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