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# Evaluating Cavern Tests and Surface Subsidence Using Simple Numerical Models

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## ABSTRACT

Cavern tests are routinely conducted to prove the integrity of solution wells and storage caverns. Because cavern tests are performed as demonstrations, test data are not fully analyzed and information that would be useful in characterizing the well and surrounding salt is ignored. Similarly, surface subsidence surveys are routinely performed over mining operations and cavern storage facilities because of regulatory requirements. The information from these surveys is often plotted and used to demonstrate that "normal" subsidence is occurring without recourse to understanding what the normal subsidence should be. Two numerical models are described that aid the interpretation of cavern test data and surface subsidence measurements. The theoretical basis, construction, and practical application of each numerical tool is discussed.

The cavern test model is used to interpret shut in and flow-rate cavern test data based on the cavern geometry, temperature and density log information, brine or gas properties, and salt modulus and creep properties. Alternatively, the cavern model can be used to estimate salt creep properties based on the cavern test data. The cavern model is demonstrated for case history test data from storage wells in domal salt and shaft closure in bedded salt.

The surface subsidence model is used to interpret and predict surface subsidence and subsurface strains, which result from underground excavation and creep of salt. The model accounts for the three-dimensional geometry of underground caverns or mined rooms, the timewise creation of the openings, and salt creep. The subsidence methodology is embodied in a personal computer program developed for the Solution Mining Research Institute. Case history subsidence data are evaluated to demonstrate the methodology and use of the numerical tool.

## INTRODUCTION

The design of conventional- and solution-mined openings in salt deposits often involves the use of numerical modeling methods to determine closure rates, stress distributions, and surface subsidence. The type of numerical modeling used most frequently is the finite element method. This method requires a substantial pre-processing effort to develop the mathematical representation of the geometry of the opening and the surrounding salt. Because a substantial effort is expended in creating models and significant costs can be involved in executing the models on the computer, exploring design options in a "what if" context is usually impractical.

This paper describes two mathematical tools that the designer can use to explore design options without the inherent difficulties and costs of rigorous numerical modeling. The tools rely on analytical expressions for stresses and strains in the salt surrounding simple geometries. Case studies are presented to demonstrate that meaningful results can be obtained using the simple tools even for complex geometries.

## BACKGROUND

Rock salts are composed of evaporite minerals such as halite, sylvite, and carnallite. When referred to as salt, the rock usually consists of halite with only minor (amounts of 10% or less) other evaporite minerals. Potash refers to a rock consisting of a combination of halite (60–75%) and sylvite sometimes in combination with carnallite (up to 15%). Rock salts are commonly found in bedded formations (salt and potash) or domes (salt) or anticline structures resembling domes (salts and potash). Rock salts are mined by both conventional and solution mining methods. Either type of extraction produces underground voids in the rock salt deposit. A common characteristic of salt and potash, as compared to other rocks, is that they are mechanically weak and creep readily under deviatoric stress conditions.

Three inelastic deformation mechanisms can contribute to the creep of salt over the range of mining and storage conditions (Munson, 1979). Each mechanism can dominate with certain stress and temperature combinations: dislocation climb dominates at low stress and high temperature (>50°C); dislocation glide dominates at high stresses (>20 MPa shear stress) and all temperatures; and an as yet undefined mechanism dominates at low stresses and temperatures. Although the undefined mechanism, which is the dominant mechanism for mining and storage conditions, has no known micromechanical model, it is empirically well-defined on the basis of laboratory testing. The usual mathematical form for expressing the relationship between the stress, $\sigma$, and temperature, T, and the resulting steady-state creep strain rate, $\dot{\varepsilon}_s^c$, for the undefined mechanism is

$$\dot{\varepsilon}_s^c = A\, e^{-Q/RT} \left(\frac{\sigma}{\mu}\right)^n \qquad (1)$$

where $\mu$ is the shear modulus, Q is an activation energy, and A and n are material constants. Typical values for the elastic and creep parameters (DeVries, 1988; Munson et al., 1989) are given in Table 1. (In the table, $\mu$, E, and $\nu$ are the shear modulus, Young's modulus, and Poisson's ratio, respectively.)

TABLE 1

Typical elastic and creep law parameter values for salt

| Parameter | Avery Island salt value | WIPP salt value |
|---|---|---|
| $\mu$ | 9.6 GPa | 12.4 GPa |
| E | 30.6 GPa | 31.0 GPa |
| $\nu$ | 0.21 | 0.25 |
| A | $1.313 \times 10^{9}$/s | $9.672 \times 10^{12}$/s |
| Q | 12.9 kcal/mol | 10.0 kcal/mol |
| n | 3.14 | 5.0 |

## Closure of storage wells

Solution-mined wells are created for two reasons: the production of saline brine for the extraction of the evaporite minerals and the creation of large storage caverns. Because the wells are located in salt which creeps under deviatoric stresses, the well will reduce in volume because of closure so long as the fluid pressure in the well is less than the prevailing far-field lithostatic stress.

Under free-flowing or uncapped conditions, the fluid pressure in the well will increase from atmospheric pressure at the wellhead to a maximum pressure at the bottom of the well according to the density of the brine (usual brine density is about 1.2 g/ml). From the wellhead to the casing seat, the brine pressure is contained by the casing. Below the casing seat, however, the pressure reacts on the cavern wall and reduces the deviatoric stress in the salt compared to an open or empty well. The brine pressure distribution in a free-flowing well is constant throughout time since brine is displaced from the well without being compressed.

For plugged wells and storage caverns, the brine pressure also increases from the wellhead to the well bottom, but in this case, the wellhead pressure does not remain at atmospheric pressure. The wellhead pressure increases as the brine or stored product is compressed by creep closure. The magnitude of the pressure increase depends on the bulk moduli of the salt and brine and the cumulative creep closure (volume reduction) of the well. For wells in which the vertical dimension is small, creep of the salt will essentially stop if the brine pressure in the well reaches the far-field lithostatic stress magnitude. For tall wells (i.e., where the top of the well is at a measurably lower lithostatic stress than the salt at the bottom of the well), the brine pressure will attain a constant distribution that minimizes the volumetric closure rate. The brine pressure at the bottom of a tall, shut-in well will be less than the lithostatic stress magnitude at the bottom of the well, and the brine pressure at the top of the well will be greater than the corresponding lithostatic stress magnitude. Hence, while the lower portion of the well continues to close by creep, the upper portion of the well expands. Eventually, the net volume change for the plugged well becomes zero and the brine pressure distribution becomes constant.

The volumetric closure of free-flowing and plugged wells and the fluid pressures in plugged wells are best calculated by numerical modeling methods that fully account for the complete constitutive behavior of salt. Unfortunately, this type of numerical modeling is complex and time consuming, and often the material properties for the salt are not well enough known to justify such detailed analyses.

## Surface subsidence

Surface subsidence results whenever an opening is created underground. At its simplest, surface subsidence is the downward motion of the earth's surface in response to the removal of rock (hence support) underground. First, there is an instantaneous (i.e., elastic) subsidence attributable to the change in stresses because of the excavation. For most salt and potash mines, the instantaneous subsidence is relatively small. Second, a time-dependent subsidence occurs that may become large (1 m, or more, is possible) and continues for tens or hundreds of years. The time-dependent subsidence is a direct consequence of salt creeping into and toward the excavated opening. Such creep will continue until the openings are completely closed and all stresses have returned to their lithostatic values.

The ultimate surface subsidence over a salt mine or storage cavern may eventually approximate the volume of rock removed from the underground. The rate of subsidence is directly related to the rate of closure of the opening, which is exponentially related to the stress concentration resulting from the extraction. Therefore, the fastest subsidence occurs over the areas with the highest extraction. The subsidence from any one opening is spread over an area much larger than that opening. Individual subsidence benchmarks can be measuring subsidence from many openings, which may have been mined at different times, with different extraction ratios and mining patterns, and in different ore grades.

Surface subsidence over vast expanses of mined area is believed to be uniformly downward and not strongly dependent on the composition of the overburden. The subsidence over smaller mined areas and mined areas adjacent to abutments is influenced both in its distribution and magnitude by the composition and constitutive behavior of the abutments and overburden material. Therefore, numerical subsidence models must be capable of including the effects produced by the abutment as well as the creep of the salt rocks.

## SIMPLE MODELS

### Closure of storage wells

The numerical model for the closure of wells under either free-flowing or plugged-well conditions is based on the analytical solution for the stationary stress distribution around circular openings in a medium that creeps. The stationary stress distribution is the one that produces the minimum creep rate for an unchanging geometry yet satisfies stress equilibrium and strain compatibility. Based on the stationary stress distribution, the creep strains and displacement rates can be calculated for any location in the medium.

The stationary stress distributions and radial displacement rate for the idealized situation are given by Van Sambeek (1986). Inherent in these solutions is that salt creep is described by equation (1) and is the von Mises effective stress. The equations for the principal stress distributions in cylindrical coordinates are

$$\sigma_r = \left\{\left(1-\frac{\gamma_b}{\gamma_s}\right)\left(\frac{a}{r}\right)^{2/n} - 1\right\}\gamma_b\, z$$

$$\sigma_\theta = \left\{\left(1-\frac{\gamma_b}{\gamma_s}\right)\left(\frac{2}{n}-1\right)\left(\frac{a}{r}\right)^{2/n} - 1\right\}\gamma_b\, z \qquad (2)$$

$$\sigma_z = \left\{\left(1-\frac{\gamma_b}{\gamma_s}\right)\left(\frac{1}{n}-1\right)\left(\frac{a}{r}\right)^{2/n} - 1\right\}\gamma_b\, z$$

and the equation for the displacement rate (velocity) is

$$\dot{u} = -\frac{\sqrt{3}}{2}\, A\, e^{-Q/RT}\left(\frac{\sqrt{3}}{n}\,\frac{\gamma_s-\gamma_b}{\mu}\, z\right)^n \frac{a^2}{r} \qquad (3)$$

where a is the radius of the well, r is the radius to the point of interest at depth z, and $\gamma_s$ and $\gamma_b$ are the stress and pressure gradients (MPa/m) for salt and brine, respectively. Integration of equation (3) over the height and circumference of the well provides the volumetric closure rate. Equations (2) and (3) are based on an axially restrained situation, which is not an actual condition because subsidence is known to occur over brine wells. Moreover, the equations are based on infinitesimal strains so changes in geometry are not accounted for implicitly.

Testing of equation (3) using measured closures in wells is difficult because the wells cannot be instrumented. Available measures are the flow rate from open wells and the wellhead pressure rise following shut in. Both of these measures can be compared to the analytical solution. Another type of measure is shaft closure in a dry mine. A shaft closure case history is discussed first because it provides a simple example for using equation (3).

### Shaft example

Closure of one of the shafts at the Waste Isolation Pilot Plant in southeastern New Mexico, is being measured using extensometers at three depths. At each depth, three, 4-point extensometers are installed. Thus, differential expansion between anchors is measured for four intervals in each of the radial directions. Figure 1 shows typical extensometer data for the three depths. For each extensometer, the plotted displacement is relative to the deepest anchor at radius 14 m (11 m into the salt from the 6.1-m-diameter shaft). The other anchors are at radii of 3.35 (extensometer collar), 4.57, 6.10, and 8.84 m. The accelerating/decelerating character of the data is attributed to seasonal variations in the intake air temperature, which causes cooling and heating of

TABLE 2

Expansion rates from extensometers in WIPP waste shaft

| Depth (m) | Expansion rate (mm/year) between indicated radius and the deepest anchor at r = 14.0 m | | | |
|---|---|---|---|---|
| | r = 3.35 m | 4 = 4.57 m | 4 = 6.10 m | r = 8.84 m |
| 326 | 0.65 | 0.44 | 0.25 | 0.09 |
| 477 | 1.57 | 0.88 | 0.62 | 0.35 |
| 628 | 3.43 | 1.96 | 0.35 | 0.49 |

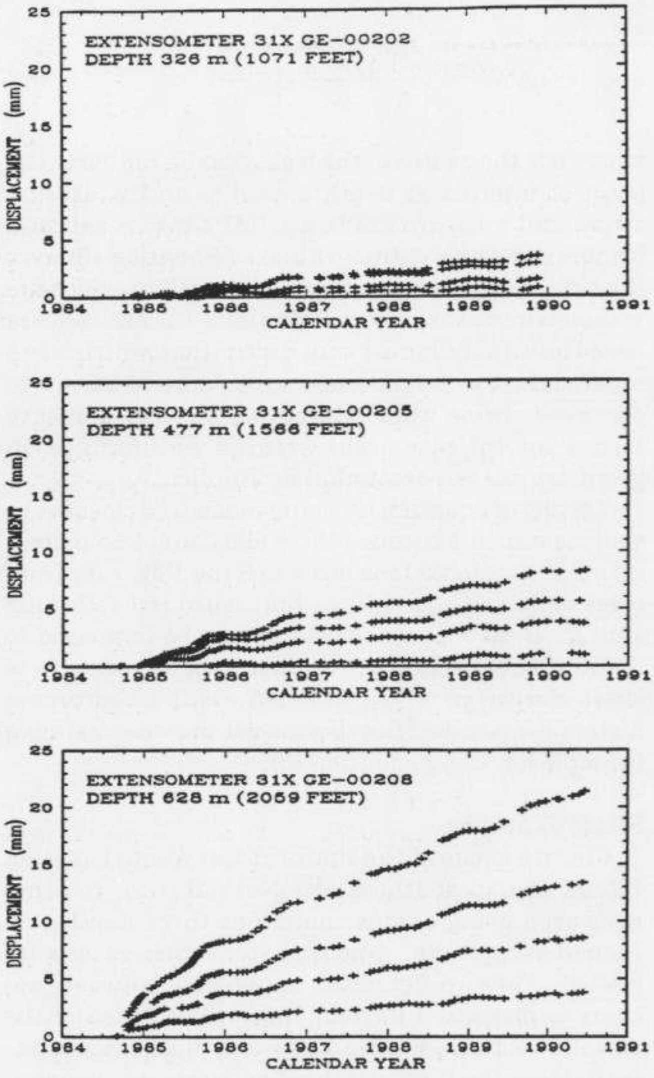

Fig. 1. Typical extensometer displacements at three depths in WIPP waste shaft (after Westinghouse, 1991).

the salt. The measured displacements did not show any directional variation, so the rates of expansion for the three extensometers at each depth were averaged over the four-year measurement period. The average expansion rates are listed in Table 2.

To test equation (3), a vertical stress gradient, $\gamma_s$, of 0.0227 MPa/m and ambient temperatures of 22.4, 24.5, and 26.7°C at the three depths were assumed. When the WIPP salt creep law parameters listed in Table 1 were used in equation (3), the calculated expansion rates were 10 to 80 times less than the measured rates. When the model was combined with a least-squares error analysis, the parameter combination that best reproduced the measured expansions was $n = 2.22$ and $A = 6.45\times10^3$ for the given $Q = 10$ kcal/mol. The lower than expected value for n (2.22 versus 5) suggests the possibilities either than a lower creep–strain-rate dependence on stress exists for this large scale, *in situ* measurement, or that the seasonal temperature variations, which produce accelerating and decelerating creep–strain rates, reduces the usefulness of a model based on steady-state, stationary stress conditions. If the temperature at each elevation is assumed to be 27°C, the temperature at the WIPP horizon, then the optimum parameter values are $n = 2.6$ and $A = 1.53\times10^5$/s with about the same goodness-of-fit as shown in Fig. 2.

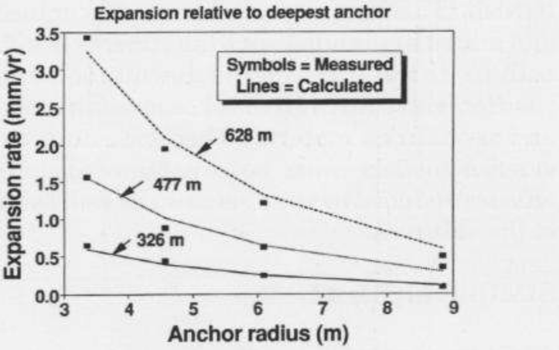

Fig. 2. Comparison of measured and calculated expansion rates for extensometers in WIPP waste shaft.

## Storage well example

Warren Petroleum Company at Mont Belvieu, Texas, has recorded wellhead pressure following shut in at two of their wells in the Barbers Hill salt dome. The shape and depth of two wells, Well 12 and Well 17, are shown in Fig. 3. Equation (3) and appropriate salt creep law and elastic parameters were used to determine the volumetric closure rate and subsequent pressure rise in the wells. The calculation was performed in the following steps:

(1) Subdivide the cavern into units in which the radius, internal pressure, far-field stress, and temperature can be assumed to be constant.

(2) For short time increments, calculate the volumetric closure using equation (3) for each sub-

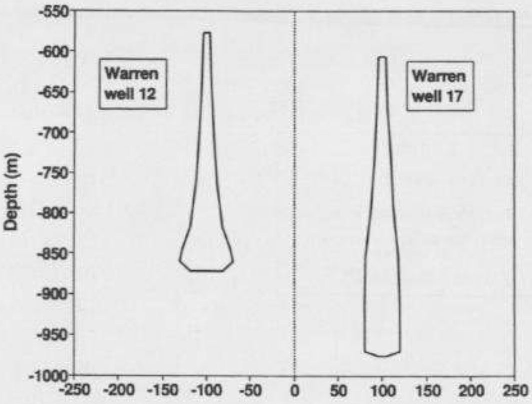

Fig. 3. Shapes and depths of Warren Petroleum Company Wells 12 and 17.

divisions' geometry, pressure and stress conditions, and temperature.

(3) Sum the volumetric closure for the entire cavern and resolve the closure into brine compression and elastic cavern expansion, which results from the cavern pressure increase.

(4) Update the well pressure distribution and repeat the process from Step 2.

Calculated wellhead pressure rise after shut in (following workovers that reduced the wellhead pressure to zero) for the two Warren Petroleum wells are shown in Fig. 4, together with the measured wellhead pressure histories. The creep law parameters used in the analysis were those listed in Table 1 for Avery Island salt, however, Young's modulus was reduced to 10 GPa to produce the results shown in Fig. 4. A comparison of results from this simple model and a more comprehensive finite element analysis is provided by Van Sambeek (1990).

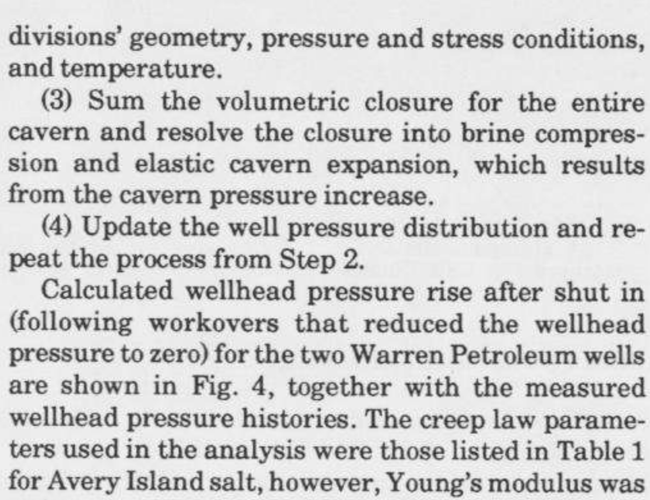

Fig. 4. Comparison of measured and calculated wellhead pressures for Warren Wells 12 and 17.

## Surface subsidence

A semi-analytical modeling approach is used to calculate surface subsidence in the computer program called SALT_SUBSID. SALT_SUBSID was developed by RE/SPEC Inc. personnel and adapted for use on personal computers under the sponsorship of the Solution Mining Research Institute (Nieland, 1991). SALT_SUBSID represents openings or mining panels as voids in a homogeneous rock mass and calculates closure of these voids based on displacement discontinuity principles (Maruyama, 1964). The geometry of an entire panel is defined by four corner coordinates, a room height, and an average extraction ratio. The geometry of a cavern is defined by its height and cross-sectional area. The representative void occupies the same area as the panel or cavern, but contains no internal support. The volume of the open void is exactly the same as the mined volume of the panel (room height times extraction ratio integrated over the area) or cavern. Because of this simplification, the entire mine complex can be included in the model. The mining history associated with each panel or cavern is also required.

The SALT_SUBSID model is based on several principles, namely:

(1) The voids representing the excavations close completely causing movement of the surrounding rock toward that location. The surrounding rock is homogeneous and the constitutive behavior is everywhere elastic.

(2) The *distribution* of the surface subsidence from this elastic response is identical to the *distribution* of the subsidence rate for time-dependent closure of the void.

(3) The void closure rate is controlled by the extraction ratio and the time that has elapsed since mining.

(4) The subsidence resulting from each individual void can be superimposed on the subsidence from all other voids. The total subsidence and subsidence rate is thus the linear combination of each individual contribution.

The SALT_SUBSID model uses three parameters to define the site-specific properties for subsidence. The three parameters are empirical and are determined by nonlinear, least-squared error fitting processes internal to SALT_SUBSID. Although the empirical constants are fitting parameters, they have a physical basis for their inclusion. The three parameters are identified in the following equation for the ultimate subsidence over the center of a panel:

$$S = Y_0 \left(1 - \exp\left(-\beta E^n t\right)\right) \tag{4}$$

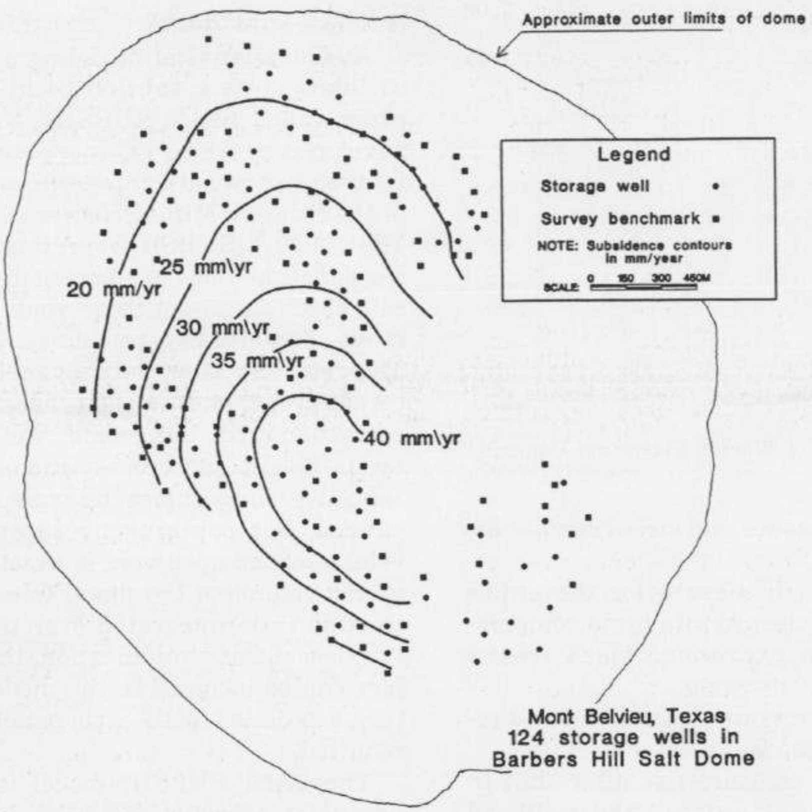

Fig. 5. Calculated surface subsidence over the Mont Belvieu storage facility (after Ratigan, 1991).

The $Y_0$ parameter represents the proportion of underground closure that ultimately shows up on the surface as subsidence. In other words, $Y_0$ is the ratio between the volume of ultimate surface subsidence and the volume extracted underground (ultimate closure volume). The parameter n (an exponent on the extraction ratio, E) is similar to the stress exponent in salt creep laws. The remaining parameter, β, is a fitting parameter that scales "time since mining," t, in the exponential function.

Because every mined area is represented by both its location and the time it is mined, SALT_SUBSID is able to separate the contributions of many mined areas or caverns to the subsidence at a particular benchmark. In fact, this is the basis for the least sum-of-squared error fitting process used to determine the parameters.

The finite element/finite difference modeling method and SALT_SUBSID, even though both are numerical analysis techniques, are fundamentally different in their approach and practically different in their use. It is virtually impossible to use finite element methods to determine the subsidence rate or amount at a particular benchmark, because finite element methods cannot efficiently represent the complicated geometry of the mines or cavern fields. Finite element methods are useful for exploring the range in subsidence rates and amounts for different excavation geometries. SALT_SUBSID, on the other hand, can consider the subsidence resulting from each individual excavation in terms of its location, extraction ratio, size, and time of mining.

SALT_SUBSID was used to examine the surface subsidence over the extensive hydrocarbon storage facility at Mont Belvieu, Texas (Ratigan, 1991). A total of 124 solution wells contribute to the subsidence being measured at 262 benchmarks. Because the wells are large and operated with internal pressurization, the closure of the wells has not changed the geometry enough to produce observable transient subsidence effects. Hence, the subsidence rate at the surface can be approximated by the integration of steady-state closure for individual wells, where the volumetric closure rate is controlled by the depth and size of each well. Figure 5 shows the calculated surface subsidence rates for the Mont Belvieu facility (Ratigan, 1991).

## SUMMARY AND CONCLUSIONS

The design of underground openings in salt often is based on the use of numerical models and material behavior models involving creep. Numerical modeling methods such as finite element/finite difference can be cumbersome to use because of the need to reflect three-dimensional geometries in two-dimensional models and the costs involved in true, three-dimensional modeling. Two simple tools were described that can assist either the designer in understanding implications of design variables or the operators in understanding behavior of underground facilities.

The first tool provides calculations of closure rates for caverns or storage wells. The second tool is used to examine surface subsidence information in terms of the individual underground excavations. Both tools are readily adaptable to the personal computer for ease of use and rapid turnaround of information.

## ACKNOWLEDGEMENTS

The permission of Warren Petroleum Company and the Mont Belvieu Industry Association to publish data from the Mont Belvieu operations is acknowledged and greatly appreciated. Cooperation within the salt industry continues to be the cornerstone for improving the safety and economics of salt mining and storage operations.

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