An Axisymmetric Method for Analyzing Cavity Arrays

F. Joseph Fischer
Shell Development Company
Houston, Texas, USA

ABSTRACT

Single, isolated cavities or small clusters of cavities far removed from the periphery of their host salt dome can usually be satisfactorily analyzed with two-dimensional methods. In some instances, three-dimensional effects of a cavity array and, perhaps, the sedimentary layers surrounding the host salt dome are important. In an attempt to capture essential three-dimensional effects within the constraints of a two-dimensional analysis capability, the concept of "axisymmetric rings" is introduced. This paper discusses the approach of axisymmetric rings and presents an example of its application, i.e., the analysis of the LOOP storage facility in the Clovelly salt dome.

INTRODUCTION

The underground storage of fluids in salt and other formations has been practiced for several decades. Typical is the seasonal, or other temporary, storage of LPG or olefins, e.g., ethylene and propylene, by the petroleum and chemical industries, in cavities leached by solution mining within bedded or domal salt formations. Such storage cavities commonly have volumes of around one million barrels (1 MMB). Within the last decade, considerable attention has been directed toward the development of large crude-oil storage facilities, e.g., the U.S. Strategic Petroleum Reserve, with cavities having volumes in the range of 10 MMB and larger. To accomplish the goal of providing hundreds of millions of barrels of storage capacity, large numbers of cavities are required. Because salt formations are limited in extent, the problem naturally arises of how to best design cavity layouts to achieve maximum utilization of available salt volume. Long-term structural stability of the storage cavities is essential, but unduly large cavity spacing, or separation, could severely limit the storage potential within, for example, a salt dome.

A salt dome containing a number of storage cavities is shown schematically in Figure 1. Salt domes available for storage purposes occur in great abundance in the Gulf Coast area of the United States and Mexico. These domes can be 5,000–10,000 feet in diameter and can extend from the ground surface to depths of 20,000 feet or more, as discussed by Halbouty (1967). Because a 1 MMB cavity might be 1,000 feet tall, its diameter would be only around 100 feet. Hence, it is obvious that for typical salt domes, many such cavities can be, and have been, located across the lateral extent (cross section) of the dome. Furthermore, different operational constraints might dictate the appropriateness of deep (~4,000 feet) or shallow (~2,000 feet) cavities. Ethylene, for example, is typically stored at a depth of around 4,000 feet to ensure that it will be in a supercritical state. This is compatible with pipeline conditions and obviously allows more material to be stored than at lower pressures associated with more shallow depths. By contrast, there is a real incentive to store crude oil at as shallow a depth as possible, in order to minimize hydraulic losses associated with cavity filling and emptying. Thus, it is not unlikely, as indicated in Figure 1, that a dome will contain cavities at more than one level.

The concern over horizontal and vertical spacing requirements for multiple cavities has always existed to some extent but has significantly increased with the need for facility design optimization, as noted above. Historical information on the performance of existing cavities is very beneficial in planning new, similar cavities. However, this information should not be used as the sole basis for designing individual cavities or groups of cavities wherein geometrical (spacing) and/or operational (pressure) conditions differ greatly from conditions of existing cavities.

As with any structure, an underground storage cavity should be examined with regard to its structural integrity. Such an examination, or analysis, however, is complicated by the fact that several significant parameters needed for such analyses are, at best, poorly understood. Among these are the in situ stress state within the salt (prior to introduction of the cavity) and the mechanical properties of

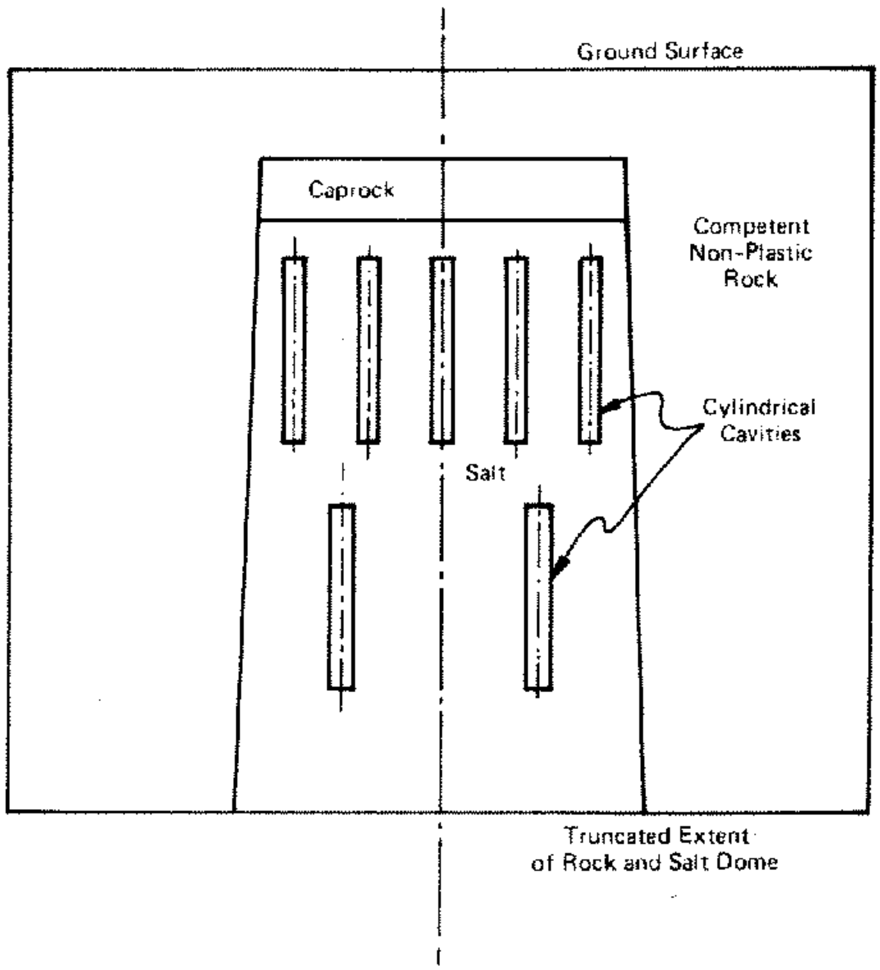

Figure 1. Schematic profile of an idealized, axisymmetric salt dome containing two tiers of cylindrical storage cavities.

the salt. Where doubt exists and the penalties for structural failure are high, conservative assumptions pertinent to unknown parameters are usually made. Several modes of structural "failure" within salt cavities have been discussed in the literature (Serata, 1978). These include significant loss of cavity volume due to creep closure, spalling of salt on the walls of the cavity due to creep rupture (allowing large blocks of salt to fall to the cavity bottom) and roof collapse. On occasion, the above events have also been accompanied by subsidence at the ground surface above the cavity.

Key ingredients to any specific cavity analysis are cavity geometry, cavity pressures, in situ stress state and mechanical properties of the salt. Once the problem of interest has been appropriately formulated, it can usually be solved to some degree of approximation with a variety of analytical and numerical methods. The most powerful of these methods are the so-called general-purpose finite-element codes, or programs, of which MARC (Marcal, 1976), ANSYS (Swanson, 1981), and REM (Serata, 1978) are examples.

The results of a stress analysis performed by the author using ANSYS is shown in Figure 2. Axisymmetry and elastic behavior of the salt have been assumed. The in situ stress state within the salt was assumed to be isotropic and to increase with depth at a rate of 1 psi/ft. This is consistent with the assumptions of $\gamma_{salt} = 144$ lbs/ft^3 and complete relaxation of shear stress within the salt over geologic time. The latter is a somewhat common, albeit unsubstantiated, assumption made by geomechanics investigators. Although yield of the salt has been precluded by the assumption of elastic behavior, an examination of the maximum shear stress within the salt gives some indication of the disturbance to the salt caused by introduction of the pressurized (brine-filled) cavity. This figure serves the following purposes:

1. It introduces the approach of axisymmetric idealization
2. It introduces the concept of examining only a portion of the salt surrounding the cavity of interest
3. It indicates large values of shear stress in the

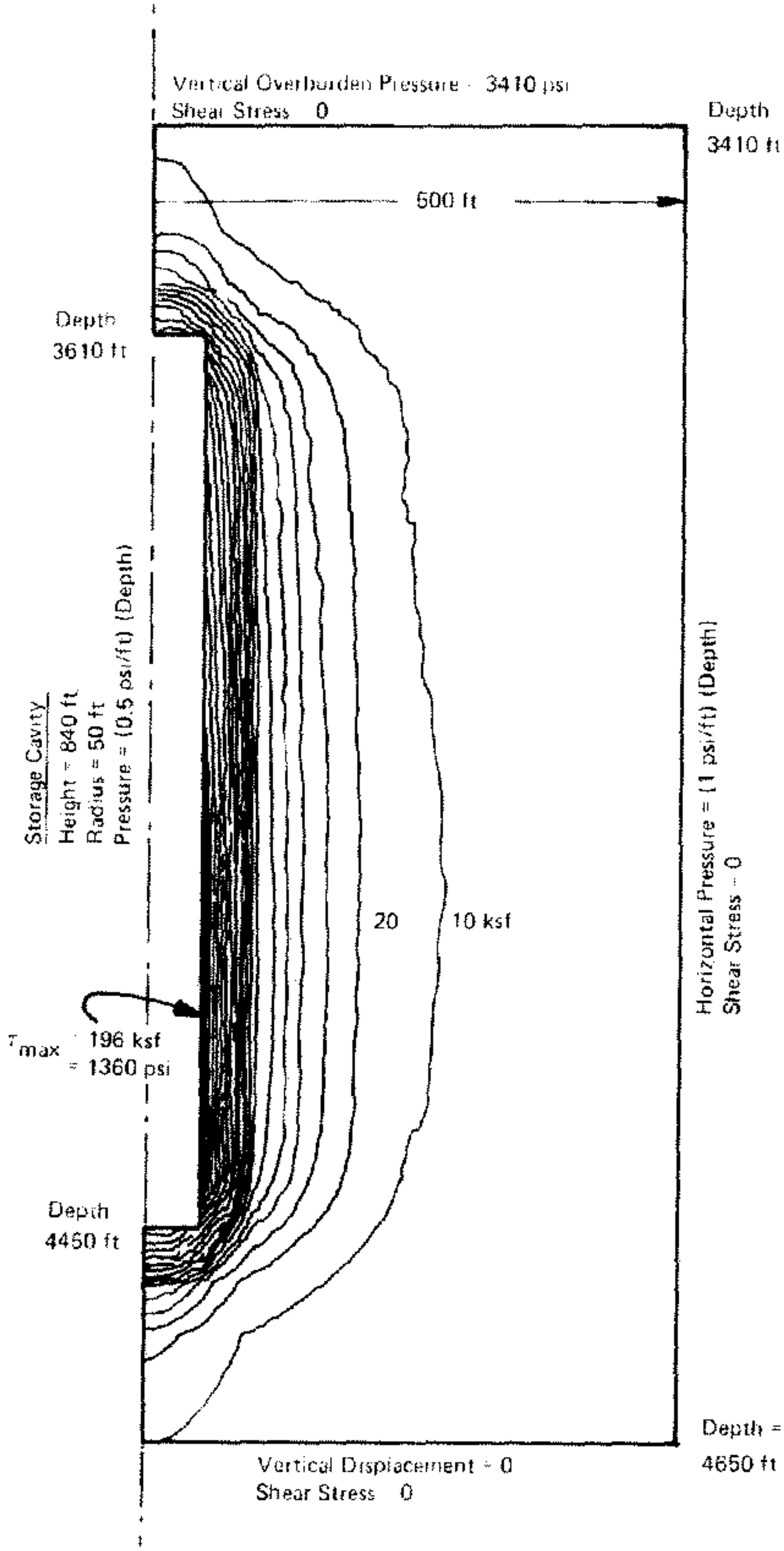

Figure 2. Contours of maximum shear stress within salt surrounding a brine-filled cylindrical cavity. Axisymmetry and elastic behavior have been assumed.

immediate vicinity of the cavity and, hence, suggests that plastic yield of the salt may occur

4. It suggests the extent of stress disturbance introduced by the cavity
5. It demonstrates the gradual vertical (axial) variation of salt stress (away from the ends of the cavity) which suggests that over this region, the two-dimensional axisymmetric analysis procedure can be simplified further to a one-dimensional radial problem assuming generalized plane strain in the vertical direction.

SIMPLE PROBLEMS AND MODELS

A thin, horizontal "slice" taken through the salt-cavity system of Figure 2, together with appropriate boundary conditions is shown in Figure 3. Provided the material behaves as an elastic material or as an elastic-perfectly-plastic material, analytical solutions for stresses and displacements exist (Flügge, 1962). For more complex material behavior, numerical solutions may be necessary. At any rate, this simple boundary value problem has been found to yield beneficial insight into the behavior of salt surrounding *single, isolated cavities*. The beneficial effects of the cavity ends are lost in this approach, however.

As seen in Figure 2, introduction of a cavity disturbs the surrounding salt for a considerable distance beyond the cavity boundary. Elasticity solutions for cylindrical cavities indicate that stresses decay as r^{-2}, while for spherical cavities, stresses decay as r^{-3}. Plasticity solutions indicate that stresses beyond the yield zone surrounding a cavity are greater than would be predicted on the basis of an elasticity solution (Obert and Duvall, 1967, pp. 170-177, and Savin, 1961, pp. 205-213). In other words, cavities in yielding materials will, in general, disturb the surrounding formation to a greater extent than if the material could not yield. Hence, the extent of disturbance by the cavity, as indicated in Figure 2, is probably less than actually occurs.

With the growing interest in arrays of cavities as opposed to single, isolated cavities, comes increased complexity of cavity analysis. One idealization worthy of mention is shown in Figure 4. Here, an infinite array of identical, hexagonally arranged, cylindrical cavities is assumed. Surrounding each cavity is a hexagonal symmetry boundary. With a little imagination, this hexagon can be transformed into a circle and the problem presented in Figure 4 can be further idealized as shown in Figure 5. This boundary value problem is identical to that of Figure 3, except for the conditions at the outer vertical boundary. Now, this boundary is at the symmetry boundary, R_s, (not $\approx 10\ R_c$) and, by symmetry considerations, $U_R = 0$, rather than having P_H specified. Again, for elastic and elastic-perfectly-plastic behavior, analytical solutions are possible. Numerical methods are generally required for more complex, i.e., realistic salt behavior.

It is significant to note that in this simple model, multiple, closely spaced cavities are explicitly considered. Again, the beneficial effects of the ends of the cavity are neglected. However, these effects can be retrieved by examination of a geometry similar to that of Figure 2 with $U_R = 0$ at $r = R_s$.

It should be mentioned that if the cavities of Figure 4 had not had a regular arrangement or if the pressures within the cavities had been different, the approach depicted in Figure 5 could not have been justified. In this case, the most simple justifiable approach would have required examination of a horizontal "slice" through the salt-cavity section of interest using the method of plane or generalized-plane strain. This is a two-dimensional method and, depending on the actual problem of interest, may or may not be appropriate. That is, important three-dimensional effects may be mistakenly neglected.

An example of a multiple-cavity problem that does not lend itself to axisymmetric, or other significant, simplification is shown in Figure 6. Here, two adjacent cavities whose stress fields can interact are shown. At a minimum,

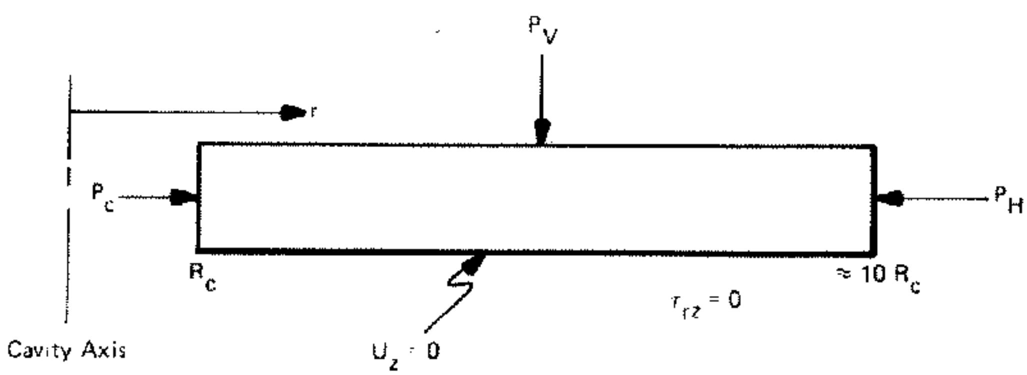

Figure 3. Simplified geometry and boundary conditions used for the axisymmetric analysis of a horizontal "slice" taken through the salt-cavity system shown in Figure 2. R_c is the cavity radius, P denotes pressure, U denotes displacement and τ_{rz} is the (r, z)-component of shear stress.

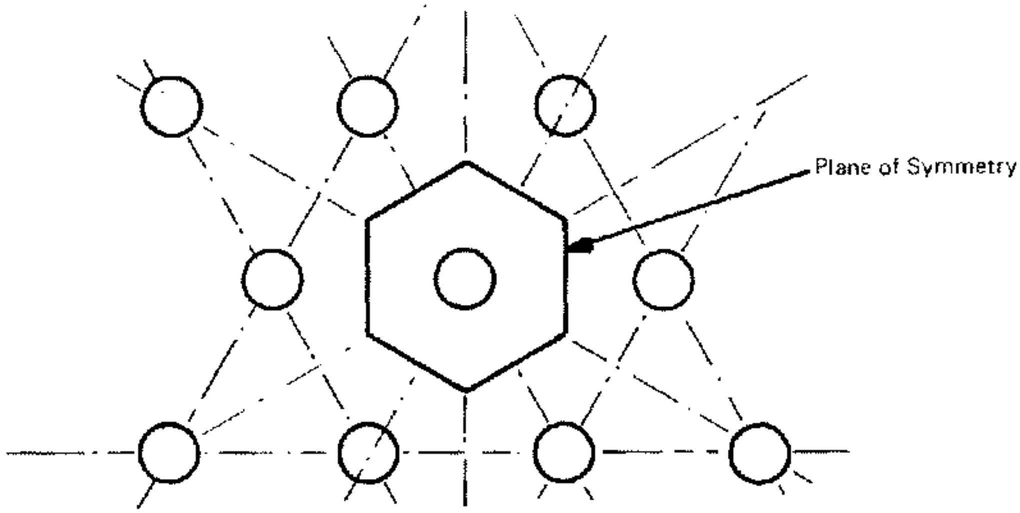

Figure 4. Horizontal cross section through an infinite array of hexagonally arranged cavities showing vertical planes of symmetry.

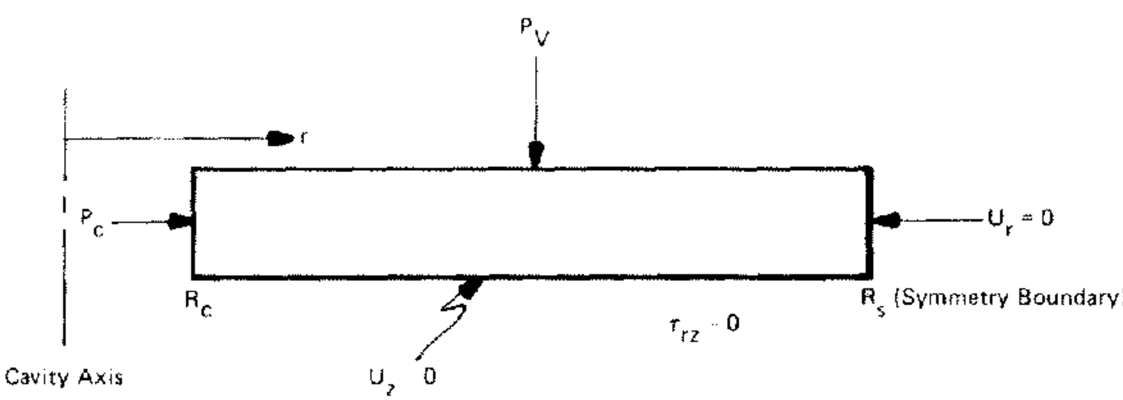

Figure 5. Simplified geometry and boundary conditions used for the axisymmetric analysis of a horizontal "slice" taken through the salt-cavity system shown in Figure 4.

it must be treated as a two-dimensional problem of plane or generalized-plane strain. Regardless of the cavity radii and/or pressures, the X-axis (as shown) is a symmetry axis. Provided $R_1 = R_2$ and $P_1 = P_2$, the Y-axis is also a symmetry axis. Such observations can significantly reduce data preparation and computing effort when using finite-element programs. If these two cavities are sufficiently far removed from other cavities and the salt-rock boundary of a salt dome in which they might reside, this two-dimensional analysis approach is both efficient *and* appropriate.

After a brief discussion of realistic mechanical models for salt behavior, some numerical results will be presented for the models/problems of Figures 5 and 6.

A MECHANICAL MODEL FOR SALT

Salt exhibits many characteristics. When loaded uniaxially, most Gulf Coast salts will display a markedly brittle behavior. When the mean stress of the salt is elevated to that present in salt domes, i.e., 1,000–4,000 psi, ductile behavior is observed, as noted by Serata (1978). Salt will flow in the presence of shear stress. The extent of this flow, or deformation, is dependent upon the level of shear stress present. Some of this flow is recoverable when the imposed shear stress is relaxed and some is nonrecoverable. Large, nonrecoverable deformations appear to occur only for sufficiently large values of shear stress. Hence, it is quite logical to postulate a yield strength for salt. One rheological model that has been proposed and

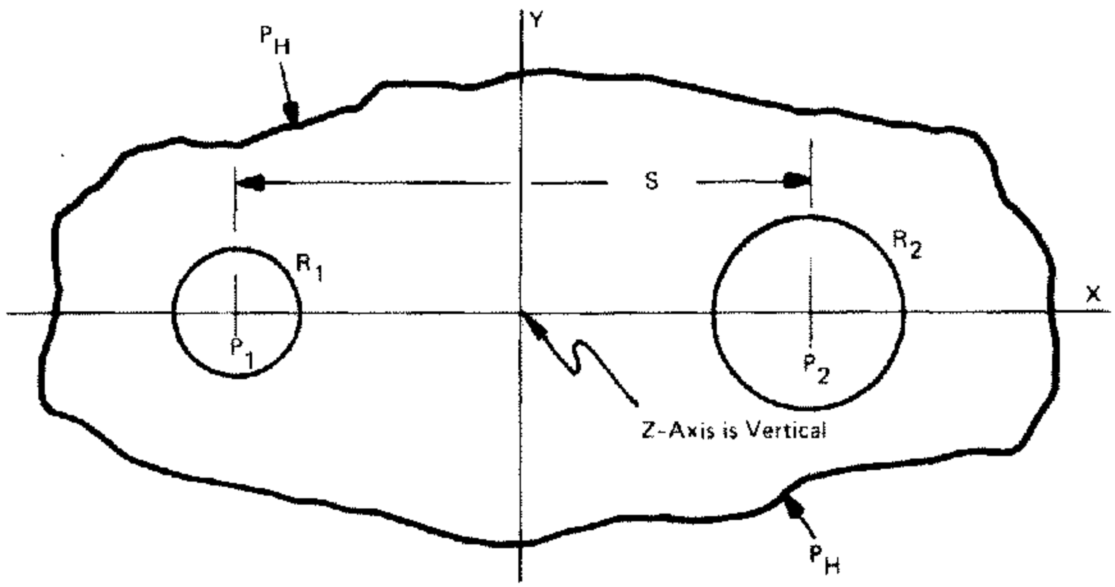

Figure 6. Horizontal cross section through two adjacent cylindrical cavities.

substantiated by numerous laboratory tests is that due to Serata (1978). One form of Serata's spring-dashpot-slider model is shown in Figure 7. If τ_0 denotes the octahedral shear stress and K_0 the octahedral shear strength, the model indicates that only recoverable viscoelastic flow will occur when $\tau_0 < K_0$ and that $\tau_0 \geq K_0$ is required for nonrecoverable viscoplastic deformation.

Typical properties for "weak" Gulf Coast salt are given in Table 1 along with properties for other materials to be mentioned later.

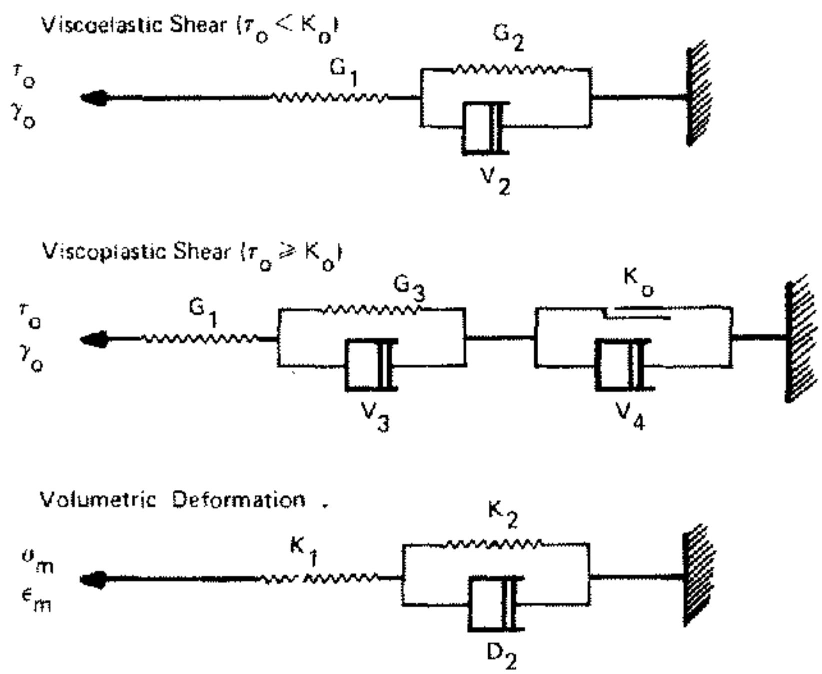

Figure 7. Rheological model for salt proposed by Serata (1978) possessing both viscoelastic and viscoplastic flow behavior.

TABLE 1

Material Properties Used for Analysis of LOOP Storage Facility in Clovelly Salt Dome

Coefficients	Units	Salt	Soft Rock	Hard Rock	Soil
G_1	10^4 psi	100.0	10.0	200.0	0.10
G_2	10^4 psi	30.0	3.0	60.0	0.03
G_3	10^4 psi	50.0	100.0	250.0	0.05
V_2	10^4 psi-day	170.0	17.0	340.0	0.17
V_3	10^4 psi-day	100.0	200.0	500.0	0.10
V_4	10^4 psi-day	140.0	280.0	700.0	0.14
K_1	10^4 psi	200.0	20.0	400.0	0.20
K_2	10^4 psi	200.0	20.0	400.0	0.20
D_2	10^6 psi-day	625.0	62.5	1250.0	0.0625
K_G	psi	600.0	1000.0	2000.0	1.00

TYPICAL RESULTS

The character of the stress interaction occurring between two closely spaced cavities is shown in Figure 8. The problem under consideration corresponds to the cavity geometry of Figure 6 where $R_1 = R_2$ and $P_1 = P_2$. Furthermore, the rheological model of Figure 7, together with the mechanical properties of Table 1, has been employed. The depth at which this cross section is taken is 2,735 feet and $P_H = P_V + 3K_0/\sqrt{2}$. The distribution of octahedral shear stress at $t = 10{,}000$ days is given for three cavity S/D (spacing/diameter) ratios. As the cavities become more closely spaced, the regions of yield (shaded) surrounding each cavity, wherein $\tau_0 \geq K_0$, coalesce. The shapes of these regions are also observed to change, as do the elastic stresses beyond the yield region. Under the assumption of vertical plane strain, Serata (1978) has found volume (or areal) closure of these cavities to be around 15% for S/D = 4 and around 17% for S/D = 2. Depending upon the failure characteristics, e.g., creep rupture, of the particular salt formation of interest, these closures and the associated strains within the salt may be of concern to the cavity design engineer. It has been advocated by some design engineers that the spacing between cavities should be large enough to prevent coalescing of the respective yield zones surrounding cavities. Such a philosophy here would require an S/D ratio of around 5–6. Such a spacing requirement would be judged excessive when compared with the spacing of existing cavities that have exhibited long-term stability.

The closure of cavities in an idealized infinite array of cavities is given in Figure 9. The model of Figure 5 together with the assumption of uniform vertical strain (generalized plane strain) was employed. The salt model and properties are the same as for Figure 8. For comparison purposes, it should be noted that radial closure, expressed as a percentage, is roughly one-half of areal closure, i.e., $dA/A = 2dr/r$ for a circular region. For $S/D \geq 4$, the radial closure for the infinite array of cavities is substantially lower than that found in the two-cavity analysis. This appears to be an anomaly until one recognizes that the symmetry planes of Figure 9 (circular symmetry boundary of Figure 5) act to "hold back" the salt from flowing inward toward the cavity. This beneficial effect dominates so long as a portion of the salt surrounding the cavity remains in the elastic state. For $S/D < 4$, essentially all of the salt throughout the cross section has yielded. Thus, competent support for the vertical overburden ceases to exist and large radial closure occurs. Based on these results, a decision should probably be made to maintain $S/D > 4$. It is also interesting to note that if vertical plane strain ($\epsilon_{zz} = 0$) had been assumed, competent vertical support would have been guaranteed (unrealistic) and the large closure seen in Figure 9 would not have been predicted; problems sometimes can be assumed away.

It is worth mentioning at this point that the problem formulation of Figure 9 both possesses and lacks conservatism. It particular,

1. End effects of cavities are ignored (conservative)
2. As applied to large but finite arrays of cavities, no

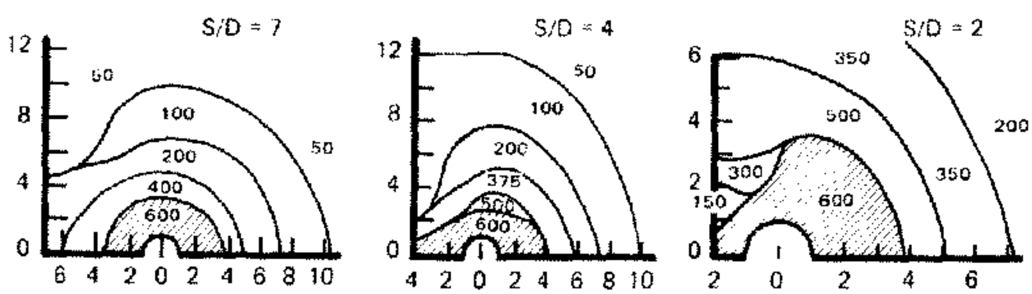

Figure 8. Octahedral shear stress distributions within salt surrounding one of two identical, adjacent, brine-filled cavities for three S/D (spacing/diameter) ratios. Plane strain was employed for the geometry of Figure 6. Mechanical properties of the salt are given in Figure 7 and Table 1. Depth = 2,735 ft and $P_H = P_V + 3K_0/\sqrt{2}$ (Serata, 1978).

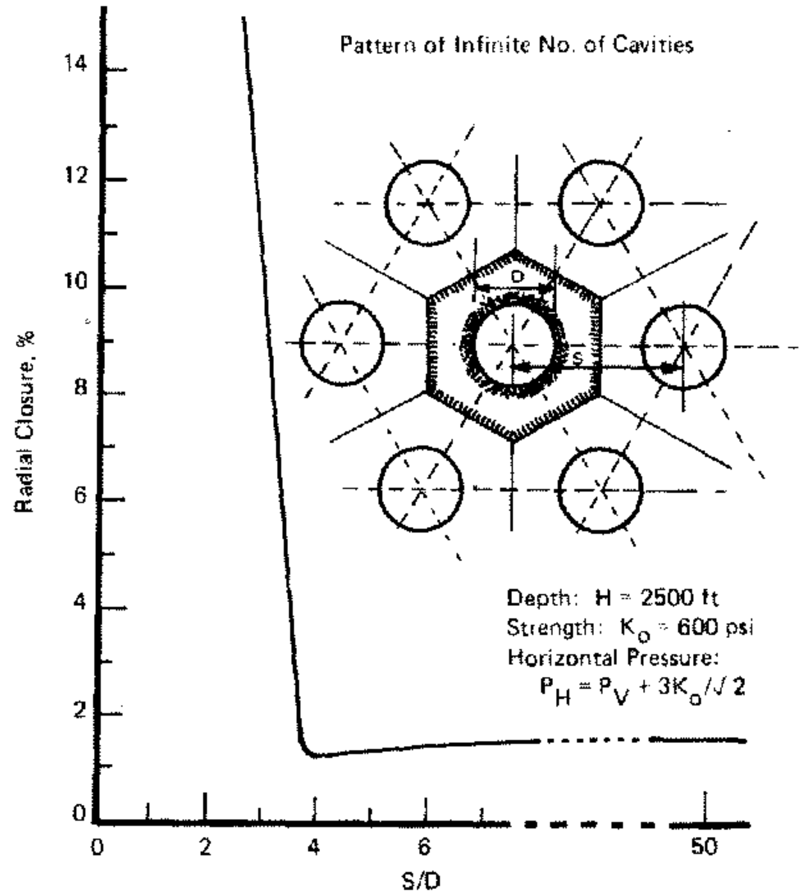

Figure 9. Radial closure of hexagonally arranged brine-filled cavities versus S/D. Generalized plane strain was employed for the geometry of Figure 5. Mechanical properties of the salt are given in Figure 7 and Table 1 (Serata, 1978).

vertical support by unyielded salt or other sedimentary layers has been considered (conservative)

3. The assumption of fixed symmetry boundaries for large but finite arrays of cavities would not be valid (unconservative). There would be a general tendency for all the cavities and salt surrounding the cavities to move inward toward the most central cavity, i.e., the symmetry boundaries would lose some of their effectiveness.

To improve one's confidence in predicted cavity behavior, more sophisticated two-dimensional or three-dimensional models are needed.

LOOP PROBLEM

The Louisiana Offshore Oil Port (LOOP) is a facility in the Gulf of Mexico for handling deep-draft crude-oil tankers having capacities up to 700,000 DWT. An integral part of this facility is an onshore storage facility which may consist of as many as 14 underground storage cavities each having a volume of 4–5 MMB. The cavities, which are nominally cylindrical in shape, are presently being created by standard solution-mining techniques. Access to existing onshore crude-oil trunklines was a key consideration in LOOP's selection of the Clovelly salt dome in Lafourche Parish, Louisiana for this storage facility.

The Clovelly dome is rather shallow; its top of salt is around 1,200 feet. It has a profile not unlike the idealized, axisymmetric dome shown in Figure 1. The dome cross section at a depth of 1,500 feet is shown in Figure 10. The minimum distance across the dome is around 3,400 feet at this depth and becomes slightly greater with increasing depth.

The proposed layout for 21 cavities with tops, or roofs, at 1,500 feet and three cavities with tops at some lower depth is also shown in Figure 10. The profile for such a layout has been given earlier in Figure 1. The circles in Figure 10 are referred to as "spacing circles." The actual cavities would be denoted by smaller circles concentric with the spacing circles.

The 21-cavity layout was not chosen arbitrarily but

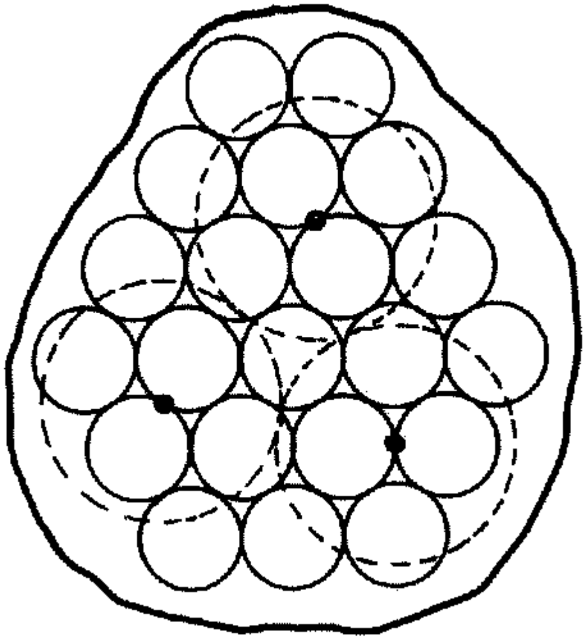

Figure 10. Horizontal cross section of the Clovelly salt dome at 1,500-ft depth showing the "spacing circles" for a 21-cavity layout at this depth and three cavities at a lower level (dashed circles). The solid dots denote locations for entry wells into the lower-level cavities.

rather is the result of the consideration of numerous operational constraints and the computed long-term response of the cavities under extreme loading conditions. Two of these considerations were

1. At least 14 cavities had to be located in the top level of the dome, preferably more
2. The upper cavities, with tops at around 1,500 feet, should not extend below 3,000 feet in order to keep fixed (steel tubulars) and variable (hydraulic power) costs at reasonable levels.

Preliminary computational results, such as those shown in Figure 9, suggested that a value of $S/D \geq 4$ was probably appropriate. Additional consideration of these results, together with the assumptions going into the analyses, suggested that adequate S/D ratios of three or less might be possible. In order to assess this conjecture, more sophisticated models than discussed previously were required. It was felt, in particular, that beneficial effects due to the salt dome caprock and surrounding sediment were likely to exist. The extent of significant stress modification surrounding a dense array of cavities in the Clovelly dome is shown schematically in Figure 11. If correct, this suggests that some vertical support for the salt surrounding the cavities may be provided by the more competent rock outside the dome. Furthermore, arching

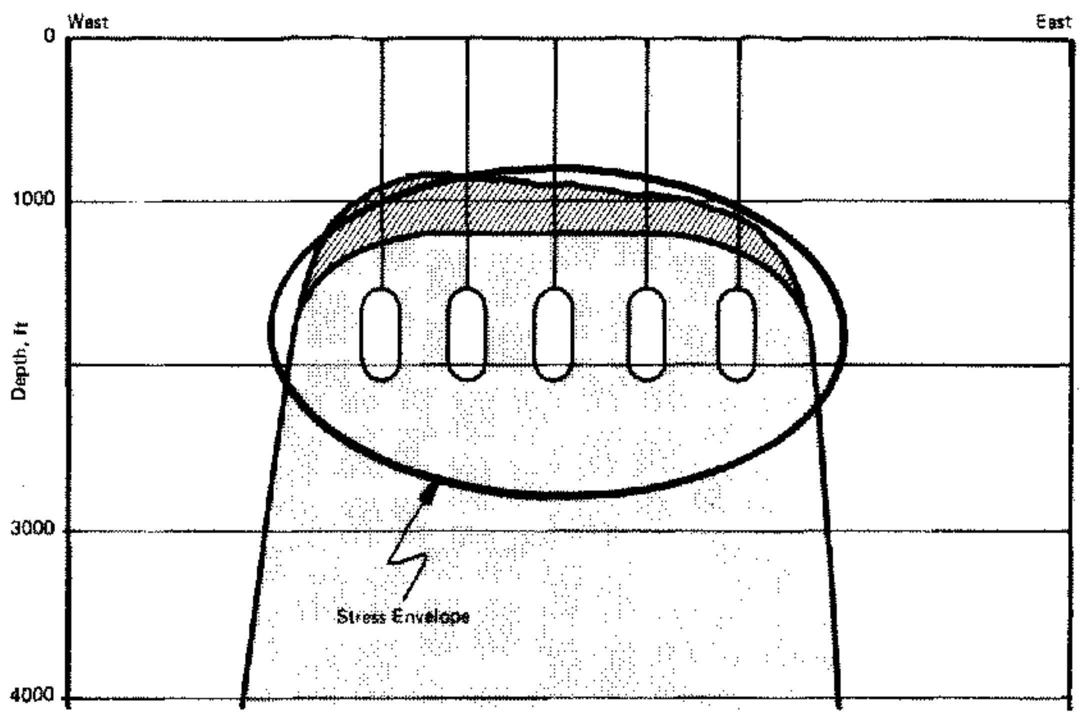

Figure 11. East-west profile of the Clovelly salt dome to 4,000-ft depth showing five of a possible 21 cavities at 1,500-ft depth and indicating the anticipated extent of significant stress modification.

above the cavity array could also act to mitigate downward loading on salt surrounding the cavities.

The above problem is truly three-dimensional in nature. Three-dimensional analysis capabilities seldom exist, are cumbersome to use, and are usually prohibitively expensive to execute. These are sufficient reasons to ask whether or not reliable results might be obtained with a two-dimensional treatment of the problem.

For similar problems, other investigators have examined horizontal and vertical "slices" through the rock-salt-cavity systems appealing to the assumption of plane strain or generalized plane strain normal to such slices. If appropriately done, such an approach would require iteration between horizontal and vertical analyses, making use of the previous solution results for the current analysis. There can be no *a priori* assurance that such an iterative scheme would converge. An alternative was thus sought. One such alternative, which heavily exploits symmetry and near symmetry, is presented in the following section.

RING IDEALIZATION

Over the depths of interest, the salt dome contours are no more irregular than shown in Figure 10. If the slight protrusion of this contour is removed, along with the two cavities its presence permits, what is left is a cross section as shown in Figure 12a. Here, 19 hexagonally arranged cavities are contained within a nearly axisymmetric column of salt (the dome). As for the cavities shown in Figure 4, a great deal of symmetry can be implied, provided the cavities are identical and equally pressured, as is assumed here. In particular, radial lines (planes) of symmetry exist every 30 degrees as indicated by the shaded wedge in Figure 12a.

Nearest the center cavity is a ring of six cavities. The radius of this ring is S, the cavity (or wellhead) spacing. Surrounding this ring of six cavities is a ring of 12 cavities. The average radius of this ring is $(2 + \sqrt{3})S/2 \approx 1.87\ S$.

The approximation of axisymmetry is introduced by replacing the discrete cavities surrounding the center cavity with "calibrated axisymmetric rings." This is shown schematically in Figure 12b. The mean radius of the inner cavity ring is that of the ring of discrete cavities it replaces, i.e., S. The radial width of this annular ring is computed to make the area of this annulus equal to that of six discrete cavities, i.e., $6(\pi D^2/4)$. Similarly, the outer cavity ring has a mean radius of ≈ 1.87 S, while its width yields an annulus with an area equal to $12(\pi D^2/4)$. With reference to Figure 12, specific dimensions for the LOOP study under discussion are

$$D = 2R_1 = 190\text{ ft} \qquad R_2 = 546\text{ ft} \qquad R_4 = 1038\text{ ft}$$
$$S = 570\text{ ft} \qquad R_3 = 594\text{ ft} \qquad R_5 = 1089\text{ ft}.$$

Admittedly, the above has been only an exercise in geometry. The task now is to "train," or calibrate, these rings to behave in a manner similar to the system of discrete cavities they are to replace. Calibration means the selection of ring surface pressures (fictitious), as shown in Figure 12c, such that the closures experienced by the central cavity and surrounding rings equal (or closely approximate) the closures computed for the discrete cavity system.

Generalized plane strain solutions were obtained for the axisymmetric geometry of Figure 12c and the 30-degree wedge shown in Figure 12a. The proprietary finite element computer program, REM, developed by Serata (1978), was used for these computations. The finite element discretization of the 30-degree wedge of salt is shown in Figure 13. For both of these analyses, the rock surrounding the salt-cavity system extended radially to 11,500 feet.

Solutions were sought near the top, middle and bottom of the proposed LOOP cavities at depths of 1,600, 2,100, and 2,600 feet, respectively. A trial and error approach yielded the pressures shown in Table 2. These pressures (probably not unique) were chosen on the basis of close agreement of cavity closures as predicted by the two methods described above; the closures at $t = 10^4$ days are given in Table 2. Also shown are assumed in situ pressures and computed radial displacements at the salt-rock interface and at the outer rock boundary ($r = 11,500$ feet).

The next step was to incorporate these calibrated axisymmetric rings into the full axisymmetric problem shown (partially) in Figure 14. The salt dome and surrounding sedimentary layers are modelled to a depth of 4,000 feet and radially to a distance of 11,500 feet. Mechanical properties of the various materials are given in Table 1. Conservatism was introduced by assuming properties associated with "weak" salt and by assuming that the lateral in situ pressure had the maximum possible theoretical value based on a value for K_0, the octahedral shear strength, of 600 psi. In particular, the in situ pressures were related by $P_H = P_V + 3K_0/\sqrt{2}$.

RESULTS

The areal closure of the center ("real") cavity is shown in Figure 15 as a function of depth for 10^2, 10^3, and 10^4 days. The maximum closure of 7% shown here can be contrasted with the volume closure figures of Table 2. Because the effect of vertical strain on volume changes in this table is negligible, the percentage volume changes are equal to percentage areal changes. It can be seen that the present, full-dome analysis yields closures less than one-half of those predicted by the next best (probably) problem formulation, i.e., that of Figure 13.

The maximum inward radial displacement of the salt-rock interface is around 1.5 feet for the present study as

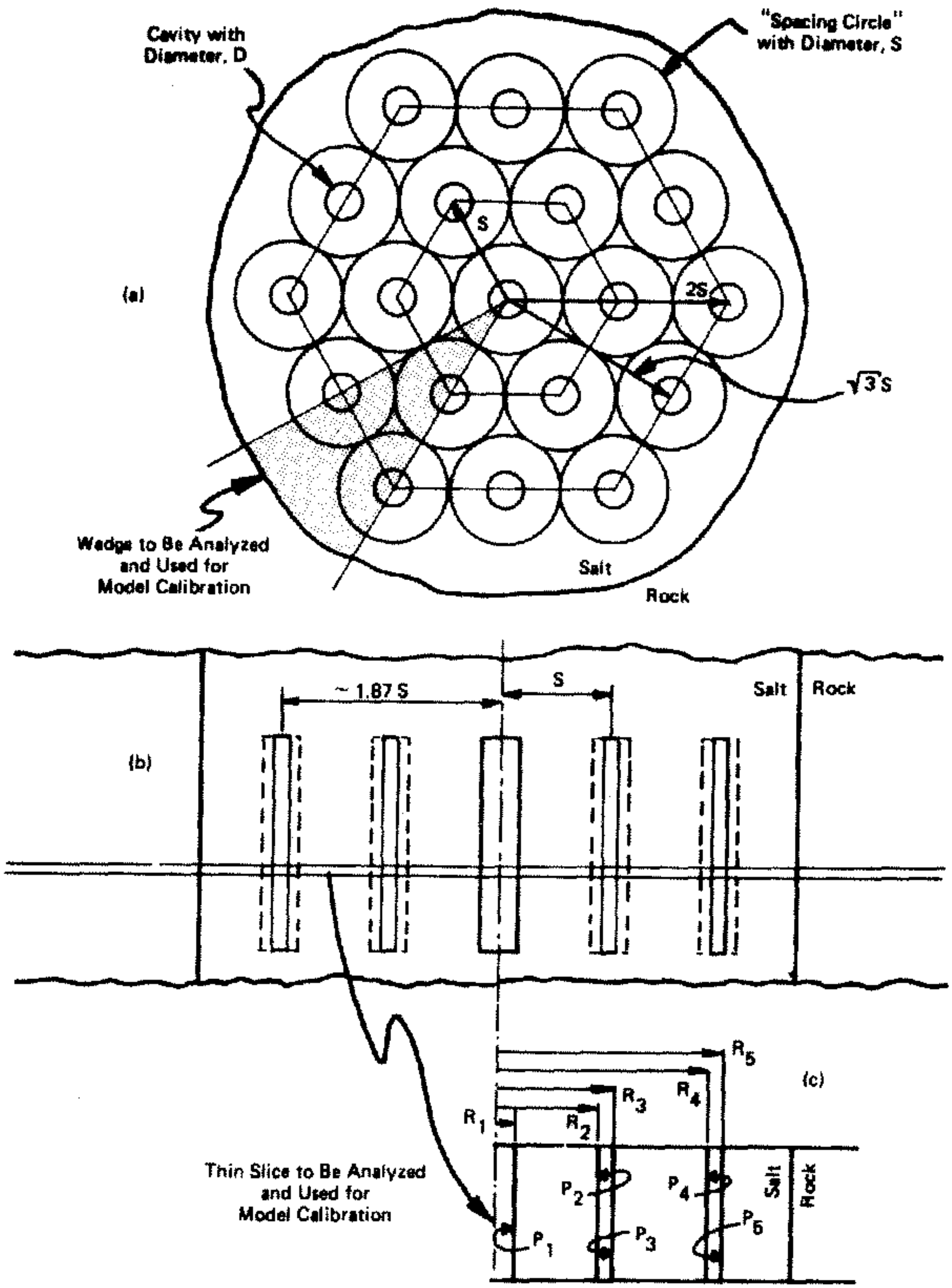

Figure 12. Idealized horizontal cross section (circular) of the Clovelly salt dome containing 19 hexagonally arranged cylindrical cavities and an axisymmetric idealization of the 19 cavities (one cavity surrounded by two concentric annular rings).

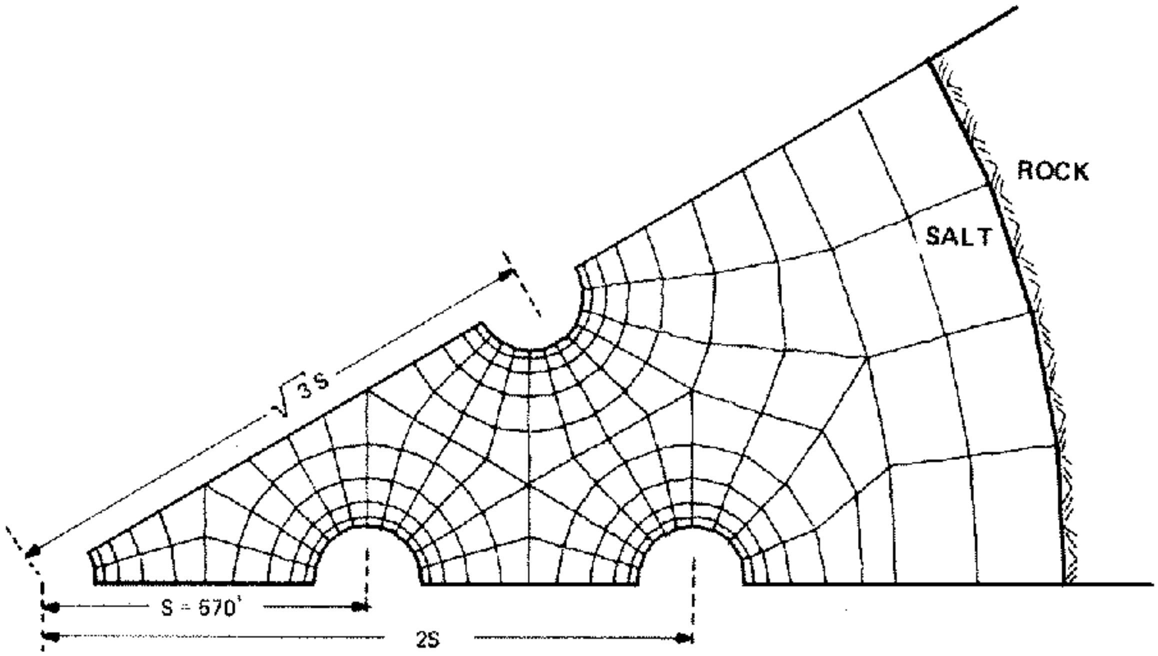

Figure 13. Wedge of 30 degrees from horizontal cross section of Clovelly salt dome shown in Figure 12. The radial lines are lines of symmetry. Wedge analyzed assuming generalized plane strain (Serata, 1978).

contrasted with a maximum value 7.78 feet given in Table 2. A probable explanation for this reduction is the presence of "solid" material above and below the array of cavities which helps to restrain the salt-rock boundary from moving inward. This is similar to the effect of the salt above and below an individual cavity in reducing the closure over the extent of the cavity.

CONCLUSIONS

For the structural analysis of single, isolated cavities or arrays of several closely spaced cavities in salt formations, relatively simple one- and two-dimensional problem formulations are probably adequate. For complex design problems, such as the one considered here for LOOP,

TABLE 2

Summary of Wedge and Axisymmetric-ring Analyses at $t = 10^4$ days

Depth (feet)	Analysis Geometry	P_V (psi)	P_H (psi)	R_S (ft)	P_{CAV} (psi)	P_2 (psi)	P_3 (psi)	P_4 (psi)	P_5 (psi)	$\Delta V_1/V_1$ (%)	$\Delta V_2/V_2$ (%)	$\frac{1}{2}\left(\frac{\Delta V_3}{V_3}+\frac{\Delta V_4}{V_4}\right)$ (%)	E_{ZZ} ($\times 10^{-5}$)	U_{SR} (ft)	U_R (ft)
1,600	Wedge	1,600	2,875	1,700	832					10.40	10.67	9.11	2.873	5.28	1.10
1,600	Rings	1,600	2,875	1,700	832	2,640	1,495	2,000	2,260	10.45	10.94	9.41	7.350	5.15	1.25
2,100	Wedge	2,100	3,375	1,800	1,092					13.25	13.59	11.59	2.439	6.36	1.34
2,100	Rings	2,100	3,375	1,800	1,092	3,070	1,981	2,500	2.675	13.16	13.69	11.57	9.303	6.05	1.56
2,600	Wedge	2.600	3.875	1.820	1.352		-			16.32	16.70	14.24	1.902	7.78	1.62
2,600	Rings	2,600	3.875	1.820	1,352	3,525	2,470	3,000	3,100	16.63	17.14	14.48	10.85	7.49	1.91

Notation:

P_V: In situ vertical pressure
P_H: In situ horizontal pressure
R_S: Salt dome radius
P_{CAV}: Cavity brine pressure
P_i: Ring pressures, Figure 12
ΔV_i, V_i: Volume reduction and total volume in ith ring of cavities ($i = 1$ for center cavity)
E_{ZZ}: Vertical (axial) strain
U_{SR}: Inward radial displacement at salt-rock interface
U_R: Inward radial displacement at outer rock boundary ($R = 11,500$ ft)

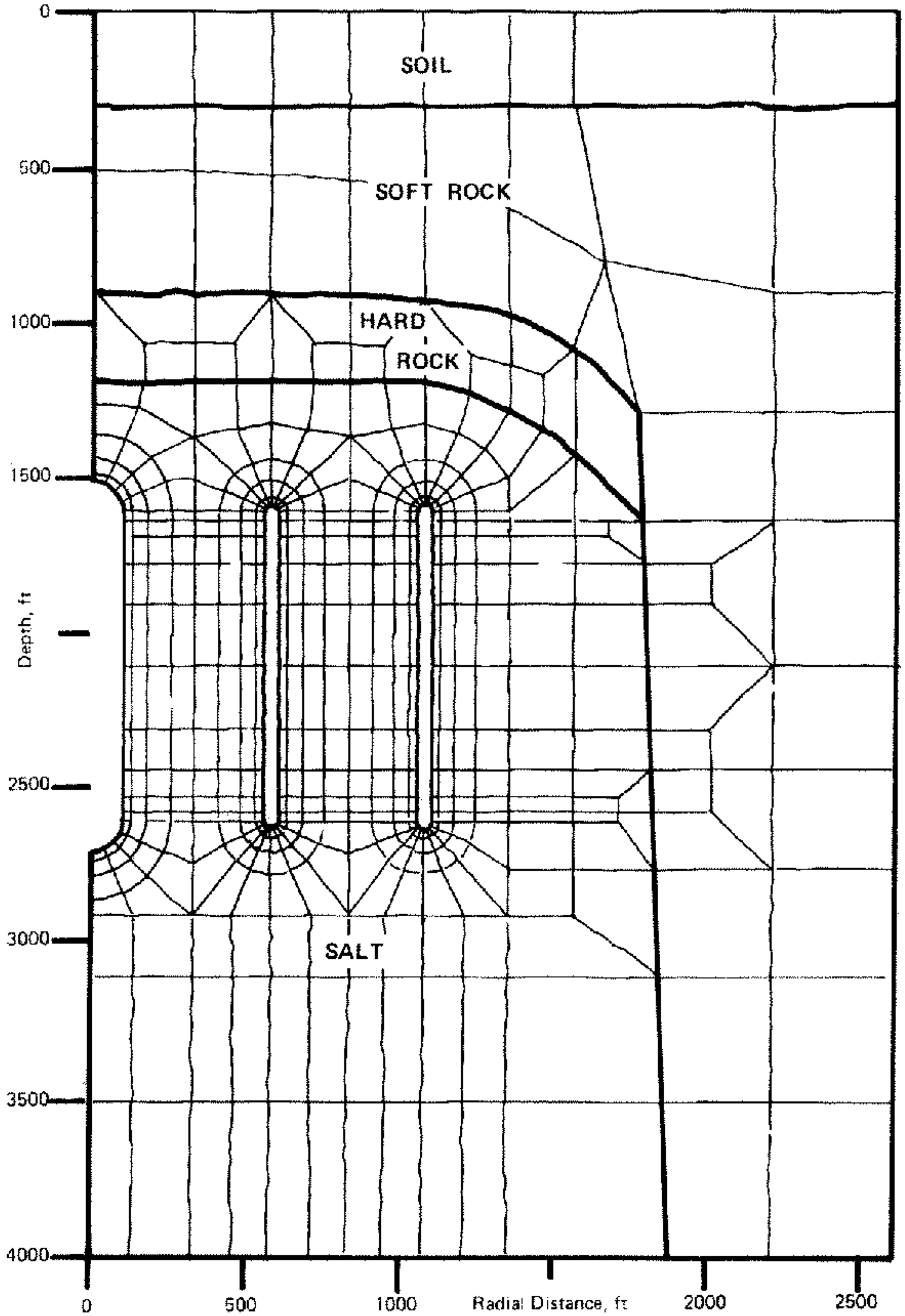

Figure 14. Profile of axisymmetric idealization of Clovelly salt dome with surrounding rock and soil. Discrete cavities have been replaced by annular rings (Serata, 1978).

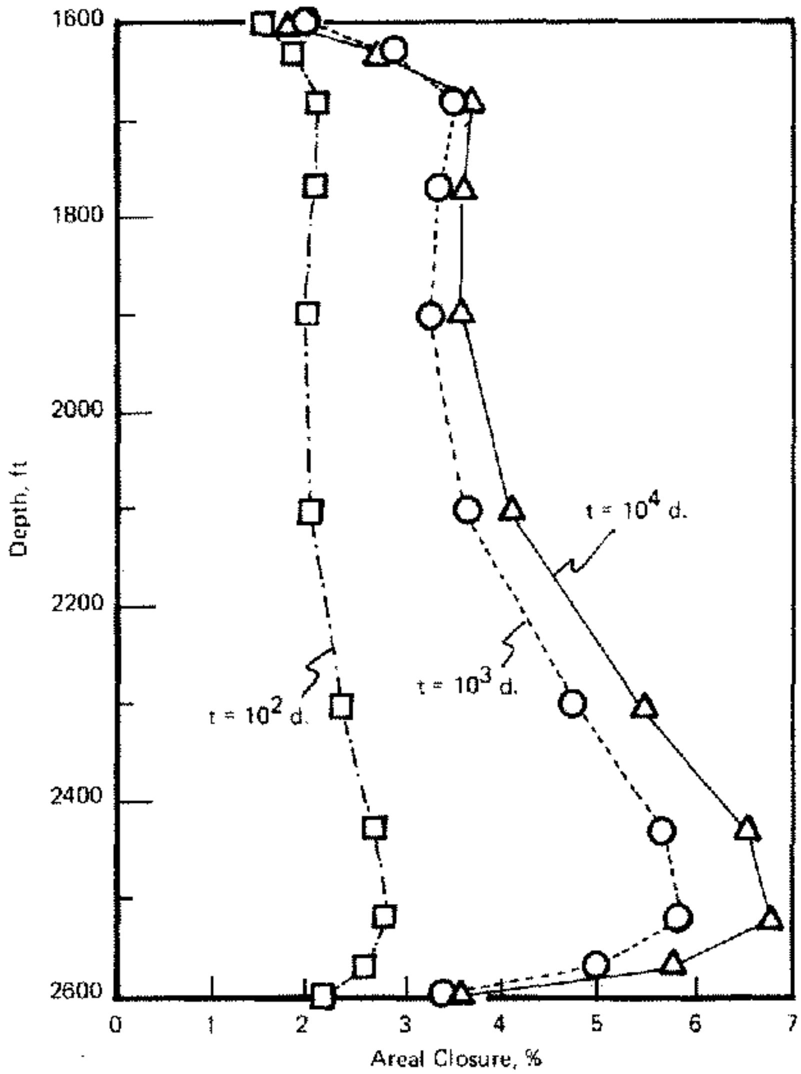

Figure 15. Areal closure due to salt creep versus depth for center cavity in Clovelly salt dome.

simple problem formulations have been shown to be inadequate, or at least overly conservative. Where three-dimensional effects are encountered, every attempt should be made to account for them; a three-dimensional problem formulation and solution method should be the last resort. An example of a "complex" two-dimensional approach has been offered here as a means of attempting to accommodate three-dimensional effects without recourse to three-dimensional solution methods.

In closing, it should be emphasized that of the several key components needed for cavity stability analyses, numerical solution techniques are probably the most well understood. It is the view of the author, however, that our understanding of the mechanical behavior of salt, including failure mechanisms, and of the in situ stress state within salt formations is much in need of improvement.

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