Model Studies of Effects of Closure of Solution Caverns in Salt Domes

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ABSTRACT

The effect of closure of solution caverns in salt domes on subsidence has been examined qualitatively by the use of time dependent two-dimensional models. Changes in stress distribution and displacements as closure proceeded were also studied.

Models were constructed of materials simulating plastic, brittle and viscoelastic deformation of the salt. Stitching wax was used to represent salt behaving plastically and a gelatin was used to represent overlying sediments. Cavities were created by removal of plugs over which the wax had been poured. Deformation in the gelatin was observed by the use of inked lines and stress distribution by the use of circularly polarized light. Models representing brittle deformation of the salt were constructed of layers of sand intercalated with clay. For studying viscoelastic deformation, gelatin was used to represent both salt and sediments. A balloon filled with water was punctured and drained to represent the cavern.

These model studies show that, for brittle failure, subsidence occurs directly over the cavern. However, with plastic deformation cavern closure occurs principally from the sides. This results in major initial subsidence overlying a zone off of the sides of the cavern. After all flow has ceased due to cavern closure, the effects of subsidence will be uniformly distributed at the surface.

It was concluded from the photoelastic study using a viscoelastic gelatin to represent the salt, that the stress gradient surrounding the cavern increased with closure. Salt however, is generally considered to behave as a plastic material.

INTRODUCTION

Solution mining of salt and the use of solution caverns for the storage of liquefied petroleum products are important technological developments. Experimental studies have demonstrated that cavities in salt domes could also be used for storing concentrated high level radioactive wastes for long periods of time. Other noxious wastes can be disposed of in this manner. The structural stability of such caverns and the effects of cavity failure require special consideration. Such a failure has occurred at least once in the Gulf Coast province. This collapse took place in a cavity mined in the Choctaw Dome in Iberville Parish, Louisiana. It is believed to have been due to the solution cavern being constructed too near the top of the salt which caused the cap rock to fail as a brittle material resulting in extreme and localized subsidence over the cavern.

Serata and Gloyna (1960) concluded that solution cavities do not collapse because a yielded zone forms around the cavity. This seems to be applicable only at a relatively great depth where the lithostatic pressure is high enough for the salt to flow plastically causing redistribution of stress. This helps to create a yielded zone around the cavity and the cavity continues to yield to the increasing stress.

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The purpose of this study was to determine the effect of size, shape and depth of solution caverns in salt domes on possible subsidence in the overlying sediments when cavern closure occurs.

The approach to this objective was limited to a qualitative study using two-dimensional time dependent models. Various kinds of materials were used to demonstrate different responses to stress in the salt. Wax was used to represent plastic behavior, gelatin for viscoelastic behavior and sand for elastic or brittle behavior. In most of the models a gelatin was used to represent the overlying sediments. The flow pattern in the wax demonstrated the direction of cavern closure. The deformation and the stress pattern in the gelatin served to indicate the expected pattern of subsidence over the salt.

The results suggest that if salt behaves plastically salt-flow into the cavern is principally horizontal which results in initial local subsidence off the side followed by a general subsidence over the dome rather than a local subsidence over the cavern. Model studies suggest that the subsidence over the salt dome would be quite small if salt deforms plastically. An experiment in which salt was considered to behave as a brittle material suggested that failure of the cavern would occur as a sudden collapse with subsidence occurring directly over the cavern.

EARLIER STUDIES

The natural state of stress in rocks below the earth's surface will be affected by creation of an opening. Changes will occur not only in the stress distribution but also in the mechanical properties of the medium itself. The creation of the cavern in a stressed elastic medium results in a redistribution of the initial stress such that a concentration of stress exists around the cavity. The magnitude of the stress concentration can be estimated by either elasticity theory or experimental methods for cylindrical or spherical cavities under any extreme pressure conditions. Salt, however, has both plastic and viscous properties depending on overburden pressure among other effects. In many instances it is seen that even when the maximum shearing stress exceeds the hypothetical maximum elastic shearing of the formation, the cavity does not collapse. This is due to yielding of the salt adjacent to the cavity boundary with the result that the stress level corresponding to an elastic collapse of the cavity is not attained. A release of stress on the boundary and a transfer of stress to the adjacent material results. This yielding characteristic of salt is particularly pronounced when the material is in triaxial compression. The behavior of salt, when subjected to triaxial compression, has been intensively investigated (Serata and Gloyna, 1960; Bureau of Reclamation, 1962).

When a cavity is created in rock salt the stress state adjoining the cavity can be anticipated to vary greatly. As a consequence the rock salt at any point will behave according to the stress environment at that point. The salt adjoining the cavern can be subdivided into zones in which the material behavior of the salt can be described as brittle (spalling occurs), plastic, or elastic. The concept of salt behaving as an elastic material in a strict sense is somewhat suspect, and perhaps a more appropriate description would employ an effective reaction relation between applied local and subsequent instantaneous deformation. In any event, the material behavior of the salt can be said to be bounded by brittle to plastic characteristics.

Extensive testing of rock salt pillar models has been carried out by Bradshaw, et.al., (1966) and Lomenick (1968), with the objective of determining the behavior of closure of mined rooms in rock salt. Their approach is essentially empirical, and consists basically of fitting a curve to experimental data which results in a relation between deformation of the salt pillar models and applied load, temperature, and time. All practical rheological models of salt are obtained in essentially the same way, since the properties of salt vary a great deal depending upon the source of the salt.

In the current study the bounding plastic behavior of the salt was modeled by wax as described earlier, and the other bounding behavior, i.e., brittle behavior, was modeled by sands and clays. In addition, the salt was represented in several models by gelatin, a linear viscoelastic material (Richards and Mark, 1966). Gelatin was also used as described earlier to model the material overlying a salt dome.

Since gelatin is doubly refracting it was possible to use the photoelastic method to obtain some estimates of the stress distribution in a viscoelastic media surrounding a cavern, and in the material overlying the salt. The stress distribution can be estimated by noting that the isochromatic bands observed in a loaded birefringent model placed in a circular polariscope correspond to lines along which the maximum shearing stress are constant. Each colored band corresponds to a different intensity of maximum shearing stress, and thus a crowding together of lines at a point implies a large stress gradient exists in the neighborhood of the point. Quantitative value of stress can be obtained by the photoelastic method in conjunction with an appropriate calibration specimen, however, this was not attempted in the current study since it was qualitative in nature.

MODEL DESIGN AND CONSTRUCTION

Fabrication.

The apparatus consisted essentially of a rectangular tank, 24 inches wide, 17 inches high, and 6 inches thick, with the front and rear enclosure made of 0.5-inch thick clear plastic supported at each end by aluminum channels (Fig. 1). Holes having a diameter of 3/32 of an inch were drilled in the center of the aluminum channels at equal intervals from the top down for 10 inches. The tank was assembled using C-clamps to secure the sides of the tank to the aluminum channels. A thin rubber strip was placed between the aluminum and plastic as a seal. A thin rubber strip and an aluminum plate was placed between the plastic and the clamps to ensure that the pressure on the plastic was uniform. This tank was mounted on a base consisting of two wooden supports which could be moved apart to provide space for insertion of a wooden plug of the same width as the tank. After the plug was positioned in the tank, the two sections of the base were moved together tightly against the plug. The tank was then sealed to the base supports by the use of silicon rubber. All other openings in the tank were sealed with silicon rubber to make the tank water-tight.

A material called stitching wax was used to represent the salt in some of the models. This was was melted and poured into the bottom of the tank. A gelatin solution was This wax was melted and poured into the bottom of the tank. A gelatin solution was sediments.

The wooden plug was designed to provide a means for forming a cavity in the wax or other material used to represent salt. This was accomplished by removing the plug after the tank was filled. Plugs of different dimensions were used for the experiments. A schematic diagram of one of these plugs is shown in Figure 2 (not to scale). A hole was drilled axially through each plug. This hole was initially closed by a plunger. The plug itself was coated with silicon grease. A thin plastic sheet (Saran Wrap) was wrapped around the plug to prevent stitching wax sticking to the wooden plug, thus facilitating easy removal of the plug. The plug prepared in this manner was pushed into the tank at the center of the tank and held tight by the two sections of the wooden base. Prior to removal of the plug to create a cavern in the wax, the

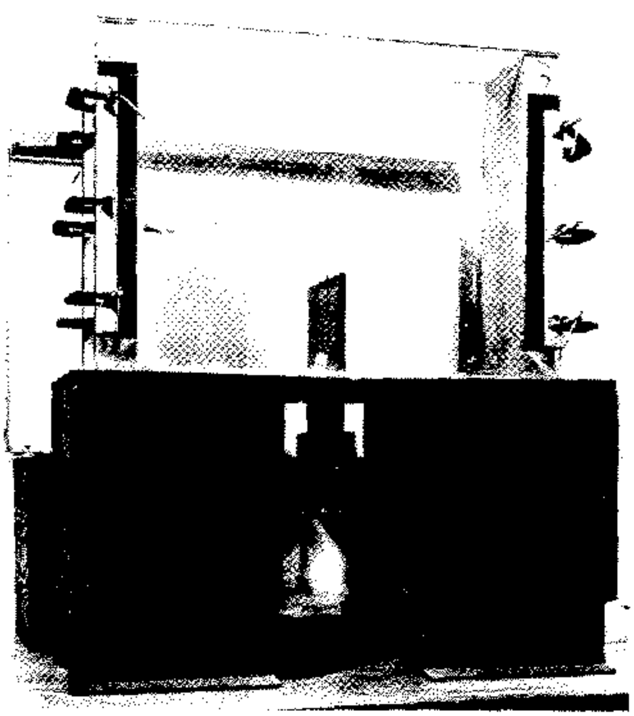

Figure 1. Apparatus used in experimental procedure.

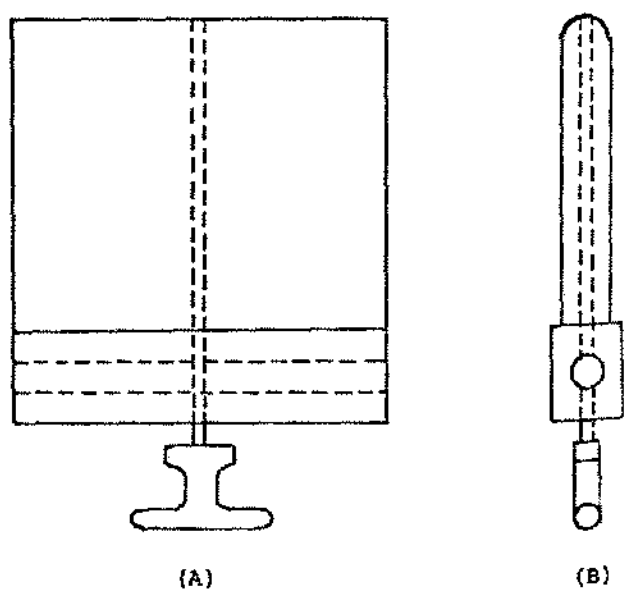

Figure 2. Diagram of cavity plug.

plunger was pulled out of the hole to break the vacuum formed between the plug and the enclosing wax.

Wax preparation.

A material called stitching wax was used to represent salt having plastic properties. The properties of this material were described by Bucher (1956). The wax was heated uniformly at 175°C for about one hour and then allowed to remain in the heated oven for another half an hour. This heated wax was then poured into the tank slowly along the aluminum sides so as to avoid trapping air-bubbles in the wax. The wax which stuck to the aluminum sides was easily chipped off since the sides had been lubricated with silicon grease. It was poured to the thickness desired for the particular model. The wax was then allowed to cool and set. The initial position of the top of the wax was marked on the plastic sides of the tank with a grease pencil.

Gelatin preparation.

A gelatin was used in some instances to represent the sediments overlying the salt. This material provided a means for observing actual strain by recording the movement of horizontal inked lines emplaced in the center of the gelatin and reaching from one side of the tank to the other (DeVillier, 1968). This gelatin has a large stress optical coefficient and thus can be used to form two-dimensional models that will be stressed under their own weight to the extent that a satisfactory analysis of isochromatic fringe patterns due to the stress distribution can be made by the use of circularly polarized light (Post, 1965).

The gelatin used in these experiments was prepared by using the constituents listed below in the weight percentages indicated:

Gelatin Powder	6%
Sodium Propionate	1%
Glycerine	4%
Hot Water	89%

This material was mixed in the following manner. First, the gelatin powder and the sodium propionate was mixed together. Glycerine was then added to the powdered mixture of gelatin and sodium propionate in a large bowl. The mixture was stirred until it became a thick and homogeneous paste. Hot water from the tap (temperature about 100°C) was added to this paste and the whole mixture was stirred vigorously until it became a uniform solution. The solution was allowed to cool to about 35°C and then poured in the tank above the wax. The gelatin solution required about 24 hours to set.

Lubrication of model.

Both the gelatin and the wax when set have a tendency to stick to the sides of the tank and thus the flow of these materials meets with frictional resistance from the sides. In order to overcome this difficulty, all of the inside faces were lubricated with Dow Corning silicon fluid to ensure frictionless flow of wax and gelatin and a thin plastic sheet was placed between the wax and the sides and was allowed to remain there throughout the experiment. This was not a perfect solution but was at least partially effective.

Embedment of inked lines in the gelatin.

A set of horizontal black lines was embedded in the gelatin to serve as reference lines for measuring deformation of the gelatin. Two methods were used to place these lines in the gelatin. In the most effective method, polyethylene tubing with an I.D. of 0.011-inch and O.D. of 0.024-inch was passed through holes in the aluminum channels and suspended across the model with weights hung on both ends. The holes were then sealed with silicon rubber. Gelatin was then poured and allowed to set. Once the gelatin had set, the tubing was pulled out while black ink was being injected into the tubing from the end that was being withdrawn. This resulted in the impregnation of a horizontal black line in the gelatin.

In a few experiments the black lines were inserted using braided nylon casting line instead of polyethylene tubing. The line was pulled out from one end and the black ink was injected from the other end into the hole created by pulling out the line. There was a tendency with this method for the ink to fail to follow the line completely through the gelatin and at times to form large "blobs" within the gelatin.

Photoelastic stress analysis.

Polaroid sheets each consisting of a polarizing sheet and a quarterwave plate bonded together were placed on both sides of the tank to produce circular polarization. The polarizer and analyzer axes were oriented parallel to each other to produce a light field isochromatic pattern when the gelatin was placed under stress.

Use of sand.

In one model, sand was used to represent salt with brittle properties. A few layers of colored sand were used to permit observation of the flow pattern and the amount and nature of subsidence. The cap rock was represented by a thin layer of powdered barite clay which effectively showed the fracturing and subsidence in this layer. Sand was also used to represent the overlying sediments in order to observe the subsidence above the cavern. A balloon filled with air was placed in the base of the sand and punctured to create the cavern.

EXPERIMENTAL PROCEDURE AND RESULTS

Experiment A

The model was scaled so that the depth of the cavity below the top of the wax, which represented the top of the salt, was eight times the width of the cavity. The width was 3/8-inch and the vertical length 4.3 inches. The thickness of the wax, which was the bottom layer of the model, was approximately 7.3 inches. This was overlain by a 7.2-inch thick layer of gelatin. There were two minor defects in the execution of this experiment but it is described none the less because certain general principles are well demonstrated. The surface of the wax was not perfectly leveled before covering it with the gelatin. The level of the wax on one side of the cavity was about 0.2 inches higher than on the other side. See Figures 3 and 6. Furthermore, a stress pattern appeared in the gelatin (Fig. 3) before cavern closure began. This was probably a result of stresses due to removal of the plug.

Figure 4 is a photograph of the model taken during closure of the cavern. Closure began in the central part of the cavity with the wax flowing in horizontally from the sides. Concurrently with closure of the cavity, the isochromatic lines mentioned above shifted. However, the resultant pattern is not as significant as in subsequent models probably due to low stress concentrations resulting from the depth of the cavity in this case. It should be noted that the wax flowed into the cavern principally from the sides.

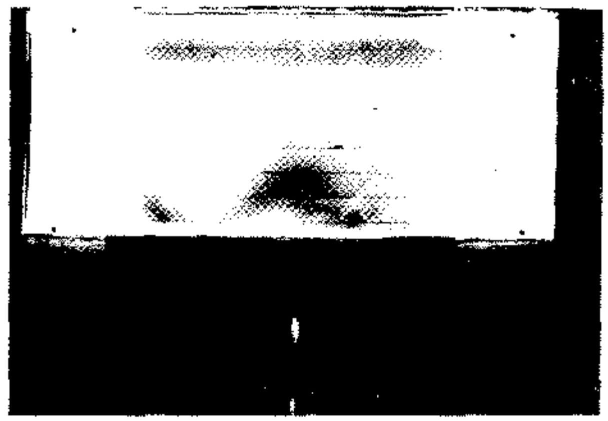

Figure 4. Flow of wax from the sides in experiment A.

Figure 5 shows the stress distribution and strain pattern in the gelatin about one hour after removal

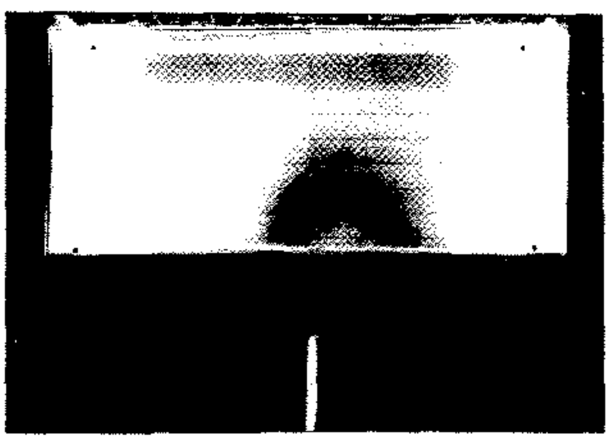

Figure 3. Model in experiment A showing initial shape of cavity.

Figure 5. Experiment A one hour after the start of cavity closure.

of the plug. The cavern had nearly closed at this time. The isochromatic lines are more diffuse than before. The black lines in the gelatin are uniformly bowed downward and show no pronounced depression over the cavern. This is also true of the top surface of the wax except for the initial irregularity. Pictures were taken at regular intervals during closure. Sequential positions of black lines in the gelatin are shown in Figure 6. After approximately 24 hours the cavity had completely closed resulting in still greater subsidence of the top of the wax. The stress developed in the gelatin had vanished showing the gelatin had reached a uniform distribution of stress. In an earlier experiment scaled identically to this one, the subsidence of the top of the wax was measured and found to be 0.08 inches. The volume of this subsided mass of wax closely approximated the volume of the cavity.

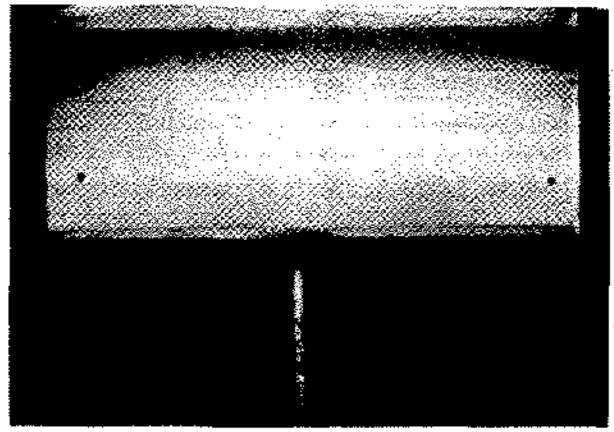

Figure 7. Initial shape of cavity in experiment B.

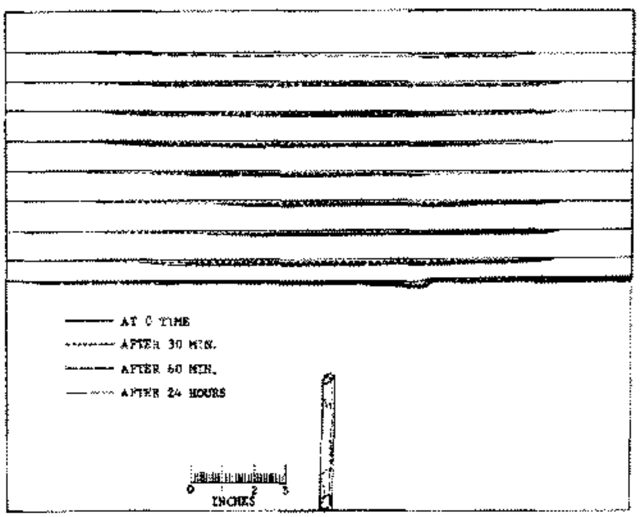

Figure 6. Sequential deformation of cavity, gelatin-wax interface and inked lines in experiment A.

Experiment B.

The ratio of depth of the cavity to its width for this experiment was changed from 8.0 used in the previous experiments to 2.4. The top of the cavity was placed 0.9-inch below the wax-gelatin interface. The width of the cavity was 3/8-inch as shown in Figure 7.

As in the earlier experiments, the wax flowed into the cavity from the sides. The cavity closed in from the center at first followed by closure at the bottom. This left an open space in the upper portion which, as in other experiments, required the longest time to close (Fig. 8). The flow from the sides resulted in a maximum stress differential in

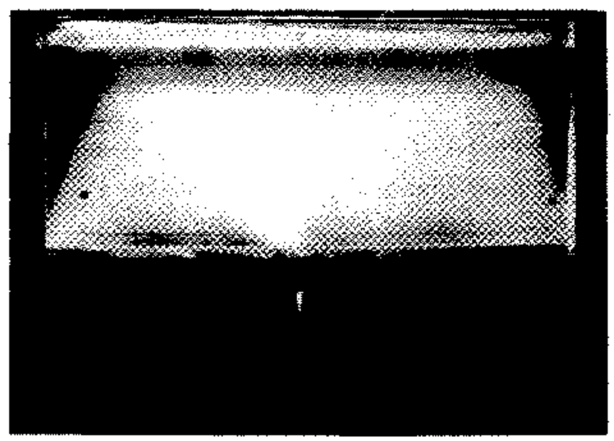

Figure 8. Intermediate stage in cavity closure in experiment B.

the gelatin just above the wax adjacent to the cavity boundary. This also caused a deformation in the gelatin shown by the lowest black line. This line was deformed generally into the shape of a bow bent downward but with a local arch over the cavern. This resulted in depressions on either side of the cavern. This strain shown by the inked line at the position adjacent to the cavity boundary was in agreement with the higher value of stress in the gelatin just above the wax adjacent to the cavity boundary (Fig. 9). The higher stress intensities shown in Figure 9 at the ends of the gelatin are due to the adhesion of the gelatin to the aluminum sides of the model. The cavity closed in completely in about one hour and 25 minutes. After about 24 hours, stress concentration in the gelatin due to cavern closure had vanished and the lines in the gelatin were uniformly curved downward being higher at the ends. The subsidence in the wax was uniformly distributed except for end effects (Fig. 10). Figure 11 shows the trace of the lines in the gelatin from the photographs taken during the experiment.

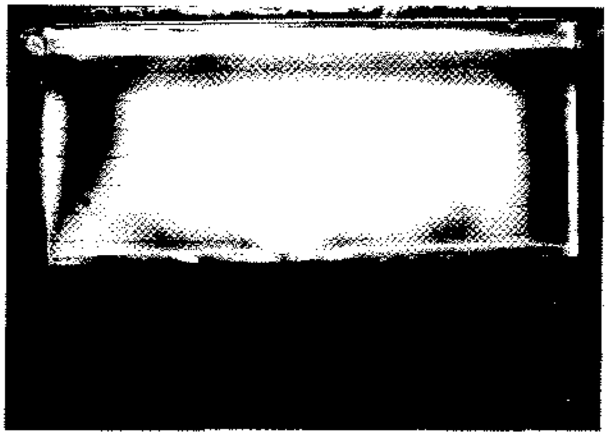

Figure 9. Stress concentration in gelatin overlying the cavity boundary in experiment B.

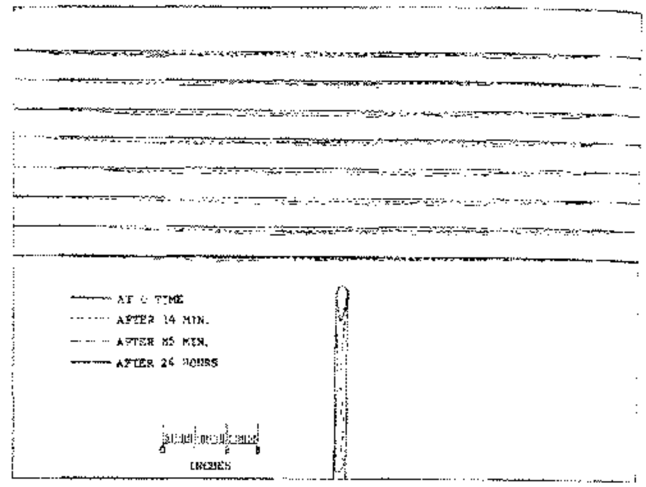

Figure 11. Sequential deformation of cavity, gelatin-wax interface and inked lines in gelatin in experiment B.

It is significant that although the top of the cavity was very near the surface of the wax, subsidence in the wax and in the gelatin was not localized over the cavity.

Experiment C.

Scaling was changed in this experiment in order to focus more precisely on the stress and strain conditions near the top of the cavity. The cavity was located so that its top would be at a depth below the surface of the wax which was equal to the width of the cavity (one inch) (Fig. 12). Initial

Figure 10. Experiment B twenty-four hours after start of cavity closure.

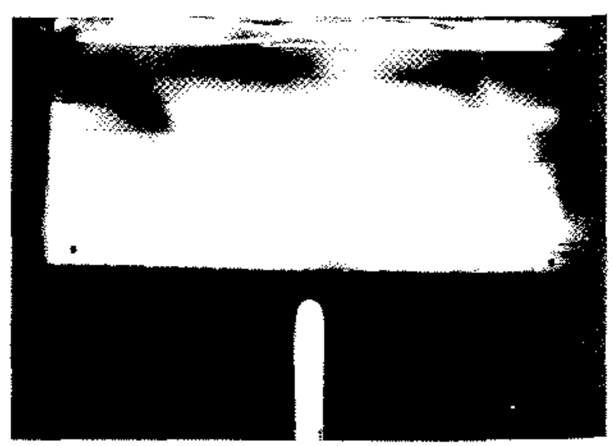

Figure 12. Initial shape of cavity in experiment C.

cavity closure was from the center followed by closure from the bottom and top (Fig. 13). The pattern of flow in the wax was similar to that observed in the first two models, A and B. Due to the larger size of the cavity, the subsidence of the upper surface of the wax and consequently the deformation in the gelatin was larger than in the first two models, A and B. Figures 13 and 14 show positions of the inked lines in the gelatin following deformation.

The lowest inked line, which suffered the maximum deformation, reached its greatest depression initially at points in the gelatin above the wax adjacent to the boundary of the cavern. This resulted in a crest over the cavern boundaries resulting from the flow of wax into the cavern from its sides. When the subsidence in the gelatin was appreciably greater above the boundary of the cavity, the strain and hence the stress was a maximum at those points. This was indicated in the diffuse isochromatic pattern in the gelatin above the boundary of the cavern. End effects were also present in the gelatin. Figure 15 shows sequential positions of the inked lines at four stages in the development of the model.

Figure 13. Experiment C eighteen minutes after start of cavity closure.

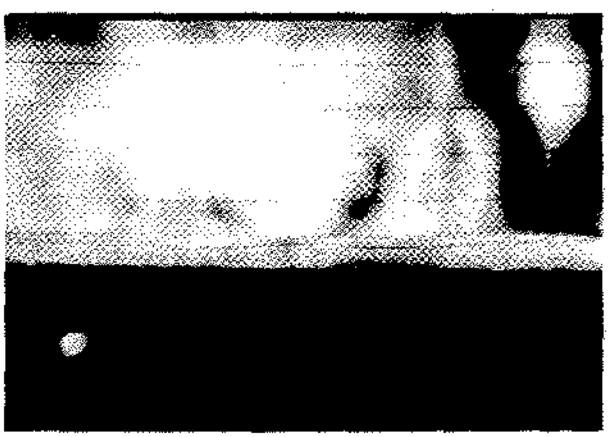

Figure 14. Deformation of inked lines in gelatin in experiment C one hour and thirty minutes after start of cavity closure.

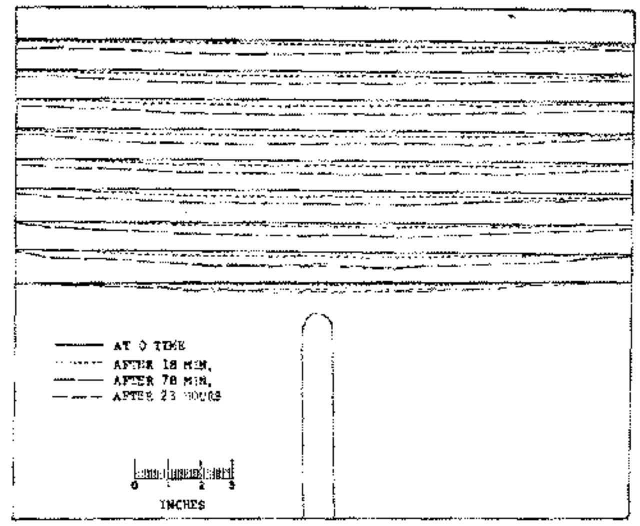

Figure 15. Sequential deformation of gelatin-wax interface and inked lines in gelatin in experiment C.

The final maximum subsidence of the top of the wax was 0.3 inch. The changing pattern in deformation in the course of the experiment is apparent. Twenty-four hours after initiation of the experiment the gelatin had returned to its original condition of stress (Fig. 16). By this time the inked lines no longer showed any local strain effects over or in the vicinity of the cavern but were deformed into the shape of a bow bent downward more in the center than at the sides due to an end effect.

Experiment D.

In this experiment the depth of the top of the cavity was established at half the width of the cavity below the surface of the wax. The width of the cavity as in Experiment C was one inch. The close proximity of the top of the cavern to the wax-gelatin interface represents an extremely vulnerable positioning of the cavity to sudden collapse of the overlying material for a real salt dome.

Figure 16. Experiment C twenty-four hours after start of cavity closure.

Figure 18. Initial shape of cavity in experiment D.

Prior to removing the cavity plug some stress developed in the gelatin producing a few random isochromatic lines (Fig. 17). For this model, the

Figure 17. Prior to creation of cavity in experiment D.

Figure 19. Movement of wax from sides and isochromatic pattern in experiment D.

plug was only partially removed leaving a cavity 3.4 inches long (Fig. 18). This was done to minimize bottom effects. However, as in the previous models, the flow of wax was fastest at the center of the cavity moving in from the sides (Fig. 19). The flow of wax at the bottom of the cavity was faster than in previous experiments dueto less friction at the bottom (in this case the friction was only against the plug). As the cavity closed in, subsidence in the wax resulted causing deformation of the gelatin. The strain in the gelatin could be observed by means of the inked lines. The lowest inked line shown in Figure 20 was deformed generally into the shape of a bow bent downward except just above the cavern where a slight reversal arched the lines upward. This suggested that the maximum subsidence of the gelatin occurred initially above the boundaries of the cavity which was the result of flow of wax into the cavity from the sides. The stress, too, was observed to be maximum at positions in the gelatin above the wax adjacent

Figure 20. Deformation of inked lines in gelatin in experiment D.

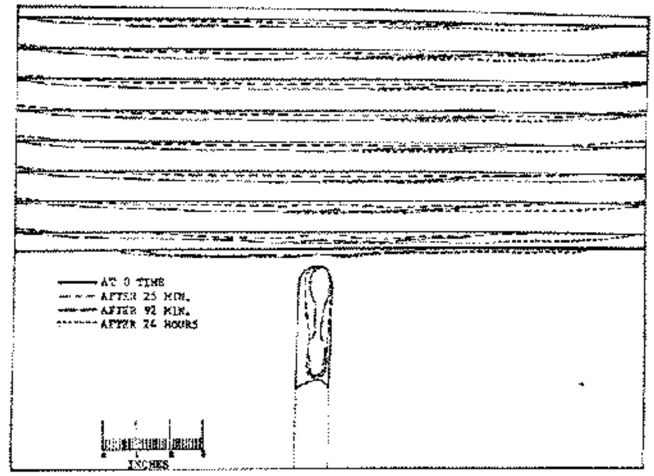

Figure 22. Sequential deformation of cavity, gelatin-wax interface and inked lines in gelatin in experiment D.

to the cavity boundaries as shown by the isochromatic pattern (Figs. 19 and 20). The stress gradient, shown by the concentration of the isochromatic lines, was highest nearest to the cavity boundaries.

After 24 hours the stress in the gelatin had nearly disappeared except that due to side effects. The inked lines no longer showed any local strain effects over or in the vicinity of the cavern but were deformed into the shape of a bow bent downward more in the center than at the sides due to an end effect (Fig. 21). Figure 22 shows the position of the inked lines and the shape of the cavity at four different times during the experiment.

Experiment E.

The purpose of this experiment was to investigate brittle failure of the cavity. Sand was used to represent salt which would behave as a brittle material in a sudden failure. A one-inch layer of dry barite clay was used to model the more cohesive cap rock. White sand with intercalated layers of colored sand was placed above the clay to represent the overlying sediments. Layers of colored sand were also placed in the sand representing the salt. The layering in the sand as well as the single layer of barite provided a means for recording the nature of deformation resulting from cavern collapse (Fig. 23).

Figure 21. Experiment D twenty-four hours after start of cavity closure.

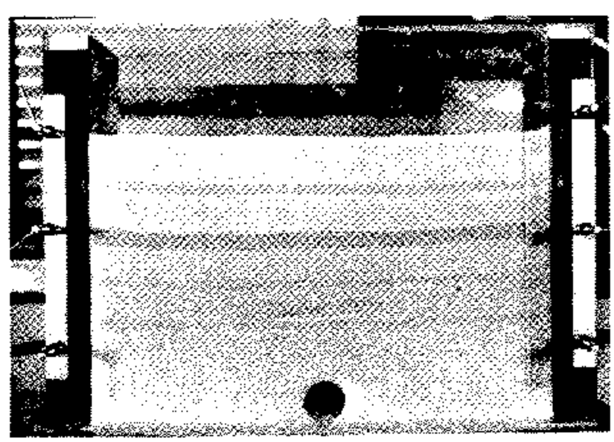

Figure 23. Sand and clay layers in experiment E prior to cavity collapse.

A cylindrical rubber balloon with a diameter of 2.5 inches, filled with air, Figure 24, was placed at the base of the sand with its long axis normal to the sides of the tank. When this balloon was punctured, the air bled off leaving a cavity of the size and shape of the balloon. The collapse of the cavity due to brittle failure was very rapid, almost instantaneous. The colored layers of sand showed the pattern of deformation and the amount of subsidence over the cavity (Figure 25). This model clearly demonstrated that for a brittle failure with the cavern located fairly close to the top of the salt, localized subsidence can be expected directly over the cavern.

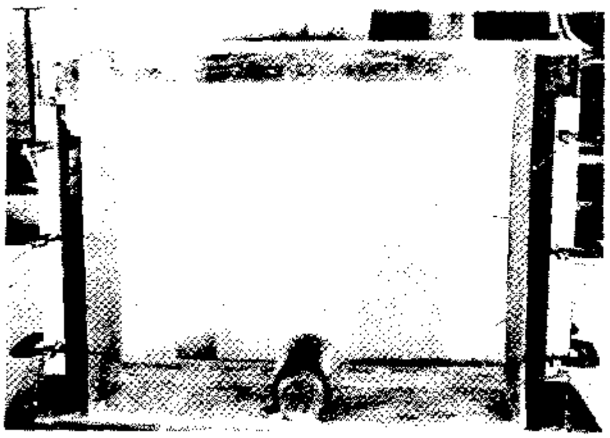

Figure 24. Rubber balloon in position in tank in experiment E.

Figure 25. Deformation following collapse of cavity in experiment E.

Experiment F.

This experiment was performed to observe the results of failure of a cavity in a viscoelastic medium. A solution of gelatin of 6% gelatin by weight was poured to a depth of 7 inches over a 2.5 inch diameter cylindrical balloon filled with water. The balloon had been placed at the base of the tank with its long axis normal to the sides of the tank (Fig. 24). This layer of gelatin represented salt with viscoelastic properties. After this basal layer had set, another layer of the same proportion of its constituents was poured over the basal layer to represent the sediments overlying the salt. An attempt to place a set of inked lines in the upper layer to serve as markers was unsuccessful. Figure 26 shows the model prior to initiation of the cavity.

Figure 26. Prior to puncturing balloon to form cavity in experiment F.

The balloon was punctured with a hypodermic needle to allow water to leak out slowly which would result in a gradual closure of the cavern. Stresses resulting from cavern closure produced the isochromatic pattern shown in Figure 27 around the cavity. Figure 28 shows the pattern about 30 minutes after the photograph in Figure 27 was made. The increase in the number of isochromatic lines about the cavity as closure continued indicates that the stress gradient surrounding the cavern increased with closure. Finally in Figure 29, showing a photograph eight days after deflating the

Figure 27. Isochromatic pattern in gelatin three minutes after start of cavity closure in experiment F.

Figure 29. Eight days after start of cavity closure in experiment F.

Figure 28. Isochromatic pattern in gelatin thirty minutes after start of cavity closure in experiment F.

balloon, many more isochromatic lines had appeared indicating both higher stresses and a higher stress gradient. The isochromatic fringes were bent into the shape of a V directly above the cavity. This suggested a faster rate of collapse from the top than from the sides, although the final attitude of the evacuated balloon in the wax in the form of a narrow vertical line suggested closure from the sides. This apparent paradox might be due to initial closure of the cavern from the top followed by a higher rate of closure from the sides. The eight days required for complete cavity closure amounted to a very slow rate of deformation in the model.

CONCLUSIONS

When the salt is represented by a material having plastic properties like stitching wax and the overlying sediments are represented by a viscoelastic medium like gelatin, a cavity created in the plastic material first closes in at the center by horizontal flow of the wax from the sides. This cavity closure from the sides results in greater initial subsidence of the top of the wax over the sides of the cavity than elsewhere. This, in turn, results in deformation of the gelatin which represents the overlying sediments. Strain in the gelatin is indicated by the distortion of the horizontal inked lines embedded in the gelatin. In experiments showing the greatest strain effects, the lowermost line which is most affected, is initially bent downward in the shape of a bow except at the center above the cavern where it is bent upward. Thus the strain is maximum at points in the gelatin above the wax adjacent to the cavity boundary.

Photoelastic results are compatible with these observations. The stresses developed due to subsidence and deformation of the gelatin produce an isochromatic pattern in the gelatin which indicates that the areas of maximum stress occur initially above the wax adjacent to the cavity boundaries. As the value of stress increases additional isochromatic lines appear. It is significant to note that although the top of the cavity may be very near the surface of the wax (Experiment D), after 24 hours local subsidence in the gelatin and wax had disappeared. By this time the top of the wax showed uniform subsidence in the form of a downward bending bow with no perturbations directly above or on the sides of the cavity. The gelatin had returned to its original condition of little or no stress and the lines in the gelatin no longer showed any local deformation at points above the wax adjacent to the cavern boundary. This was also the case for the other models that showed localized initial subsidence.

The experiments using wax to represent the salt as a plastic medium suggest that if a cavity would eventually close, subsidence would occur with a varying pattern through time. One might expect a period early in the history of closure in which maximum subsidence would occur over the salt adjacent to the cavity rather than over the cavity, itself. However, the final result long after cavity closure begins would simply be a small amount of subsidence over the entire surface of the salt. The amount of this final subsidence will be relatively insignificant for cavity volumes in the 10,000,000 to 15,000,000 cubic feet range.

Experimental work demonstrates that if the salt behaves as a brittle material, a cavity in the salt could collapse very rapidly. The more cohesive cap rock would then fracture intensively and it would suffer local subsidence over the cavity. The overlying sediments would also subside directly over the cavern although the magnitude of such subsidence may be less than that in the cap rock or in the salt. For sudden collapse of a cavity located fairly close to the top of the salt, local subsidence can be expected immediately over the cavity. The failure of a cavity in the Choctaw Dome in Iberville Parish, Louisiana probably represents this kind of failure.

The effect of cavity closure in a viscoelastic medium is distinctive. As cavity closure occurs in such a medium, the medium surrounding the cavern is stressed and an isochromatic pattern develops in the model around the cavity. The concentration of isochromatic lines increases with the closing of the cavity showing an increase in the stress gradient around the cavity. Thus the stress gradient surrounding the cavity increases with closure if the material has viscoelastic properties.

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