Rock Mechanics Instrumentation for Salt Mining

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ABSTRACT

Measurements of deformations and stresses in the rock salt around underground salt mine openings are made easier by the fact that the salt will creep under pressure. Several types of instruments are described which will permit these measurements to be made; instruments for measuring deformations are the tape extensometer in conjunction with borehole extensometers of both the rod and wire varieties. For measuring rock stresses the instruments discussed include the photoelastic stressmeter and hydraulic borehole gauges. Rock bolt tension meters are also described. The emphasis is on low cost and simplicity of operation. Where possible enough detail is given to enable the rock mechanics engineer to build much of his own equipment.

The methods in which the instruments should be used are discussed with practical examples of how certain conditions of instability can be detected. Also discussed are the criteria of stability by which mine design can be optimized so that the best percentage extraction ratio is obtained.

INTRODUCTION

Despite the fact that theories of plasticity are always complicated and often unusable, the actual measurement of ground movements and pressures in salt mines is a relatively simple matter when compared with similar measurements in hard rock mines. This is because the ground movements involved in salt mining are usually large and uniform. The stability of the underground openings and pillars can be correlated with observed movements of roof sagging, roof/floor convergence, pillar dilations, stresses in pillars and rock bolt loads. Tl movements proceed with time, perhaps at a co stant, diminishing or accelerating rate, dependi upon the stresses involved. The possibilities of i vestigating the effect on present and future mi stability of such factors as mining methods, pe centage extraction, opening geometry, roof sp width, geologic variations, etc., are obvious, as a also the economic benefits to be gained from su a knowledge.

The instrumentation required for making tl measurement is not expensive. Single point ar multiple point borehole extensometers, conve gence rods and dilation pins plus a tape extensor eter will suffice to measure the movement Stresses and stress changes can be measured usi photoelastic stressmeters and hydraulic boreho gauges. Rock bolt load cells are useful for dete mining the efficiency and adequacy of rockbolti support systems.

The following paper describes the use of su instrumentation. The aim is to provide enough d tail that the rock mechanics engineer can buil many of his own instruments and make the nece sary measurements.

If the benefits of a rock mechanics program a to be realized it is essential for the rock mechani engineer to have the full support and cooperati of the mine management. In particular the should be a means of drilling the necessary instr mentation boreholes which is independent of th production equipment. If this capability is not pr vided the chances are that the scope of the instr mentation program will be compromised alon with its usefulness.

INSTRUMENTATION TO MEASURE MOVEMENTS

The tape extensometer.

This instrument is designed to measure in between two points which may be spaced at from about 2 feet to 50 feet apart. The accuracy is around ±0.005 to ±0.010 inches which is adequate for the kind of movements which will be measured.

The instrument, shown in Figure 1, incorporates a 50 foot measuring tape, a tensioning spring, dial indicator, adjusting screw and thrust bearing. The measuring tape has a series of holes spaced at regular intervals (say 1½ inches) in which a peg on the end of the instrument can engage. The outer end of the tape and the other end of the instrument both have hooks which can clip onto eyebolts. The eyebolts are threaded and can be screwed into anchorages in the rock. The anchorages can be fabricated from ordinary rockbolt parts.

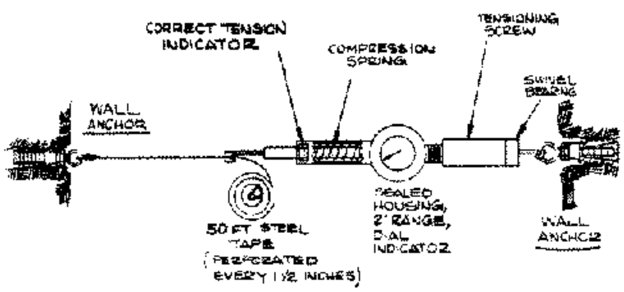

Figure 1. Tape extensometer.

The instrument is read by hooking the peg into one of the tape holes; the adjusting screw is rotated until an index mark shows that the correct tape tension has been achieved. The correct tension is checked by supporting the instrument in the hand and by swaying it away from and then back towards the correct position in which it is in line with the two measurement points. When this is done the spring tension index marks will appear to move apart and then together again. When the index marks move apart and then come back to be exactly opposite without crossing over each other no matter how the instrument is positioned then the reading of the dial guage is the correct reading. Tape tensions in the region of 15 to 20 lbs. will take out much of the sagging in the tape.

The rod extensometer.

This instrument is designed to measure in between two points which may be spaced at from about 6 to 15 feet apart. It consists of a series of telescoping aluminum or stainless steel tubes which can be adjusted to different lengths and are held in position by a pin which can engage any one of a series of holes in the telescoping sections. One end of the rods has a spring loaded plunger the movement of which is sensed by a dial indicator. To read the instrument it is first adjusted to approximately the right length. One end of the instrument is then placed in a fixture anchored to the rock. The other end is carefully snapped into place into another fixture anchored into the opposite surface of the roadway. The accuracy of the instrument is about the same as that of the tape extensometer. It is mainly used for roof/floor convergence measurements since in the horizontal position it is difficult to make accurate measurements. In fact it is a much more cumbersome and less versatile instrument than the tape extensometer.

The temperature variations normally experienced underground are usually so small that their effect on the dimensions of the measuring instruments is negligible. This is especially true of borehole devices. Because of this and because the required precision is not fantastic it is permissible to use materials such as aluminum (anodized) and stainless steel. If the measurements are required to be very precise then materials such as invar may be used, or corrections be made for temperature changes, but in most cases the errors inherent in simply positioning the instruments will be larger than any temperature effects.

BOREHOLE EXTENSOMETERS

The tape extensometers can be attached to fixtures anchored in the walls, roof and floor of the underground openings. Measurements from these fixtures may be unduly influenced by local fracturing which allows the immediate skin of the opening to move in ways not characteristic of more deep seated movements. Hence it is necessary to have measurement points located at depths away from the surface.

Rod type borehole extensometer pins.

Figure 2 shows a type of borehole extensometer pin which can be fabricated from easily obtainable rockbolt parts. The main parts are rockbolt shells, extension rods and couplings to which are added

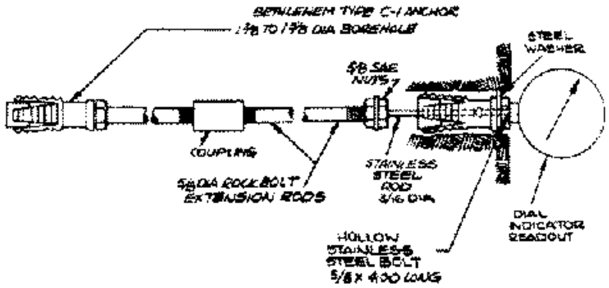

Figure 2. Borehole extensometer rod type.

S.A.E. nuts and washers. The only machining required is to drill and tap a hole in the end of one rod to accept a stainless steel rod. Also the anchor at the mouth of the hole uses a 4" stainless steel bolt which has a ¼ inch diameter hole drilled through it and its outer face milled flat.

The rods can be very rapidly installed using only a socket wrench with extension bar and long nosed pliers. The entire system lies inside the borehole. Both factors make the system extremely useful for setting close to the working faces.

The readout is by dial indicator and the reading is accurate to ±0.001 inch. Various lengths of rod can be used in the same locality. This involves the drilling of multiple holes. In hard rock this very often is prohibitive both in terms of time and money. In soft rock such as rock salt the difficulties of drilling a borehole are considerably less especially if the rock mechanics engineer has his own drill.

Wire type borehole extensometers.

Obviously, the more instrumentation that can be packed into one borehole the less time and money will be spent drilling. Also if one needs to measure movements at great depths away from the opening then the drilling of many long holes involves too much expense. Multiple Point Borehole Extensometers are available to permit several measurements to be made in one hole. In such systems, it is generally more convenient to measure the distance from the down-hole anchor to the mouth of the hole by means of a wire instead of a rod.

Various degrees of sophistication are available. Perhaps the simplest system is one consisting merely of borehole anchors and wires. The outer ends of each wire has a collar fixed to it which can be gripped and its position measured relative to a borehole collar anchor (Potts, 1957, 1964; McClain, 1964). A more complicated system would include an instrument head at the mouth of the borehole which holds each wire in tension by means of either hanging weights, coil springs or cantilevers. The head would also provide a surface to which wire movement could be referenced. The readout could be mechanical using a dial indicator, depth gage or micrometer. Further sophistication would include a remote readout of wire movements using electronic sensing devices. (Sellers, 1968).

Borehole anchors.

The main requirements of borehole anchors are that they be easy to install and that they maintain a good grip on the walls of the borehole. Mechanical setting is to be preferred over grouting or cementing techniques. Also if the anchor can be set without having to rotate it, this will make it easier to keep the various wires untangled. Figure 3 shows three very simple borehole anchors. The first one is made from a strong steel torsion spring. The

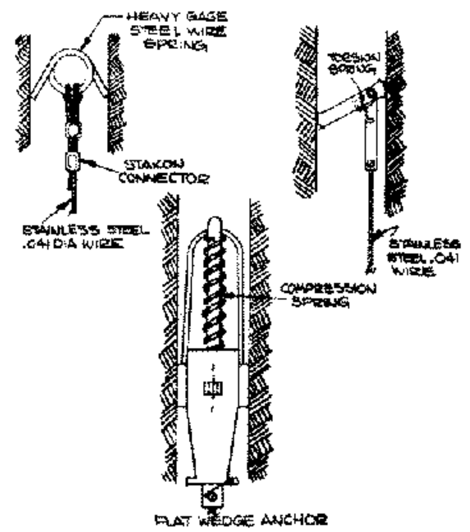

Figure 3. Simple borehole anchors.

second one has a spring loaded strut which jams across the hole when the wire is tensioned. The third type has a spring loaded bail which permits movement into the hole but becomes wedged firmly in the hole when the measuring wire is tensioned. All these anchors are very easily installed simply by attaching a wire to them, pushing them into the borehole to the required depth using setting rods and then tugging on the wires to set the anchors.

Other anchors can be used especially in long holes where higher wire tensions are required to overcome sagging. For very long holes a groutable type anchor is generally the best then the extensometer can be preassembled outside the borehole using plastic pipe to space the groutable anchors. All the measuring wires are contained within the plastic pipe. The entire assembly can be pushed into the borehole and then grouted in place. The instrument head is attached later. A groutable borehole anchor is shown in Figure 4. This figure also shows a mechanical anchor which is designed to be spaced by plastic tubing. The mechanical anchor system

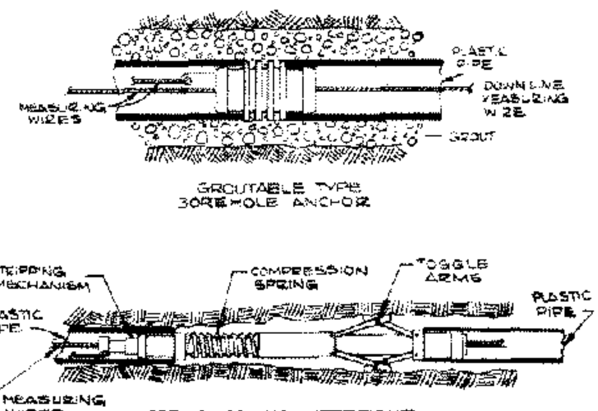

Figure 4. Borehole anchors for long boreholes.

like the groutable anchor system can be assembled outside the hole. The assembly is pushed into the borehole with the anchors locked in a collapsed position. When at the right depth the anchors are each tripped by pulling on the measuring wire. This releases a latch and allows the toggle arms to spring out and bear against the walls of the borehole. This type of anchor assembly is particularly useful where the time available to install the instrument is limited.

Measuring wire.

Stainless Steel Wire with a diameter of around 0.040 to 0.050 inches is suitable for use as a measuring wire. The breaking strength of the wire is in the region of 400 lbs. and the modulus is high being around 29×10^6 psi. It will resist corrosion and maintain a smooth exterior. It is light enough that it does not sag excessively. The wire is easily obtainable; about the only problem is that it is sold in coils of about 2 feet diameter. The wire is very lively and unless restrained it will tend to spiral and may coil around neighbouring wires. In a wire type extensometer it is extremely important that the wires do not become entangled. When installing the borehole anchors great care should be taken to keep the wires separated. One excellent technique is to pass the wire through a wire straightener as it comes off the coil. As more and more anchors are installed in the hole the wires can be cut off at different lengths for easy identification and taped together in an orderly and carefully preserved sequence. If each borehole anchor incorporates a plate in which there are several holes, these holes can be used to separate the wires.

If each wire is always read at a constant tension then there will be no correction for wire stretch. If the tension in the wire is allowed to vary, then a correction for wire stretch is required. The correction depends on the type of wire, the spring constant of the tensioning spring, the length of the wire, the inclination of the wire to the vertical and the anchor spacing which will affect the amount of wire sag in non-vertical holes. As an example the wire stretch correction factor for a stainless steel wire 0.041 inch diameter and a spring constant of 18 lbs. per inch would be $(1 + 0.005L)$ for a vertical orientation and $(1 + 0.0075L)$ for a horizontal orientation. L is the length of the wire in feet. Thus for very long wires the correction factor can be quite large. Although wire stretch acts to decrease the sensitivity it also increases the range of the extensometer which is very often a desirable feature in long holes.

Instrument heads.

The simple system of borehole extensometers, which uses borehole anchors and measuring wires only, requires a portable instrument head with which each wire can be gripped, in turn, and subjected to a constant tension. The instrument head can be located in a fixture which is permanently anchored in the mouth of thy borehole. The tension is applied to the wire by some adjustable screw mechanism and the correct tension is indicated by an index mark. When the correct tension is reached a dial indicator is used to measure the position of the wire collar relative to the mouth of the borehole. The tape extensometer previously described can be used for the application. All that is required is a light aluminum stirrup which will screw into the borehole collar anchor. The stirrup is about 2 feet long and has an eyebolt at its outer end to which the tape extensometer can be attached.

Figure 5 shows one possible configuration for an extensometer head which applies a constant tension to the measuring wires by means of lead

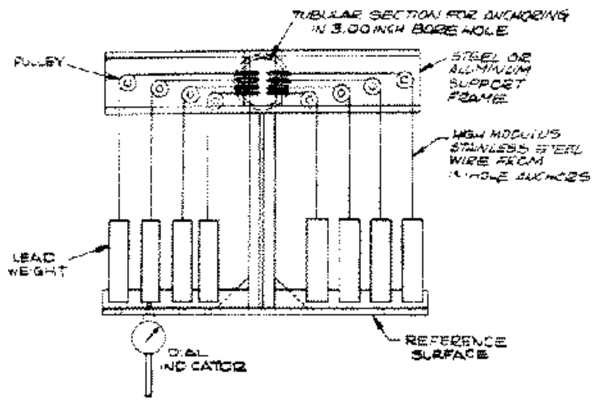

Figure 5. Typical 8 point weight extensometer.

weights. The entire assembly must be fixed firmly in the mouth of the borehole. The position of the weights can be measured using a dial indicator. The main disadvantage of this system is its bulk which makes it vulnerable to damage by blasting, moving vehicles and mine personnel. A much less bulky method for tensioning the wires is by springs. Figure 6 shows a coil spring type extensometer for tensioning as many as eight wires. The wires pass through and are fixed to spring loaded plungers. The movement of the plungers relative to the body of the instrument is measured by a dial indicator. The instrument head is clamped into the mouth of the borehole by a mechanically actuated collar anchor. A screw-on cap protects the instrument head from dust and moisture. The entire head can be recessed into a reamed-out section at the mouth of the borehole.

For remote readout capability the movements of the wires can be sensed electronically and the signals fed via an electric cable to a readout box. Figure 7 shows one type of electronic extensometer manufactured by Terrametrics. The wires are tensioned by means of eight strain-gaged cantilevers. This particular instrument can measure cantilever deflections of 0.00005 inches. This sensitivity plus the low inertia and friction in the

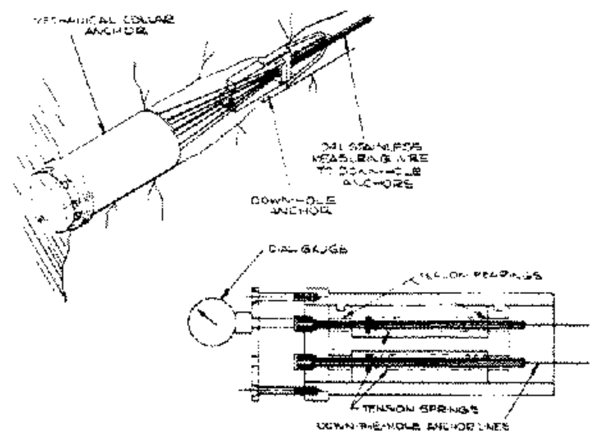

Figure 6. Coil spring type MPBX.

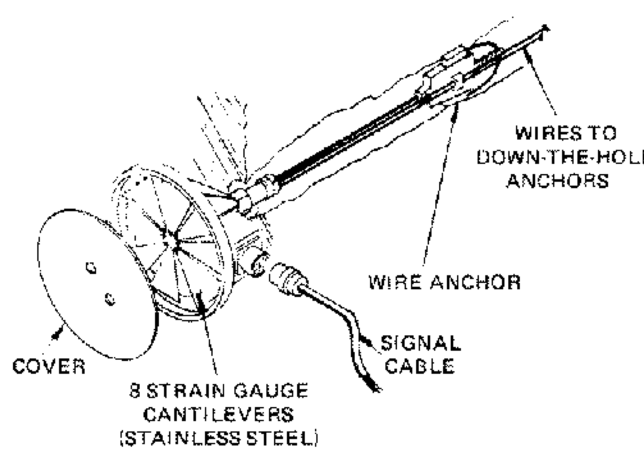

Figure 7. Strain gauged cantilever type MPBX.

instrument head makes the instrument particularly useful for high accuracy work (Benson, 1969).

Convergence pins.

A useful measurement is that of roof/floor convergence (Wieselmann, 1968). This can be done using the equipment described earlier, i.e., a tape or rod extensometer in conjunction with rod type borehole extensometer pins. In fact this method should be used because it can be used at points very close to the working faces. Thus very little of the total roof/floor convergence will be missed. Occasionally, however, in isolated or abandoned areas of the mine, or in areas with high room heights, it may be more convenient to use convergence pins. These can be made most conveniently from aluminum tubes which can be purchased in sizes which telescope together. Two such tubes are used, one tube is anchored in the roof and the other in the floor. Again it is best to anchor the tubes mechanically at points away from the surface of the opening. Figure 8 shows a typical convergence pin system. To each tube is clamped a collar. As the roof converges to the floor, the collars move closer to one another and the movement is measured using either a depth gauge or dial indicator. Naturally the rods are vulnerable to damage and cannot be installed close to the working faces.

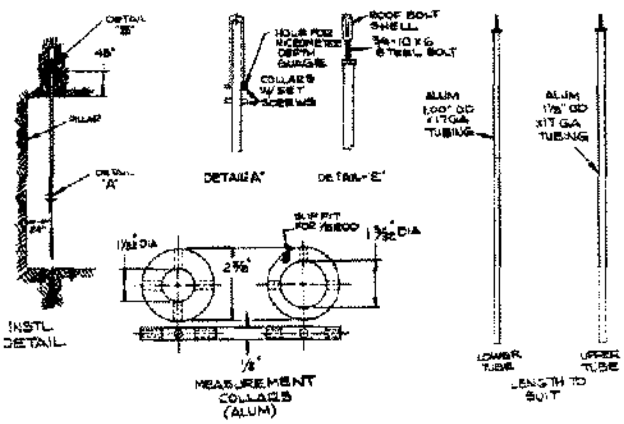

Figure 8. Convergence measurement rods.

INSTRUMENTS TO MEASURE ROCK STRESS CHANGES

Rock salt in situ will creep under the influence of internal stresses. Generally the shear strength of a rock salt is low and it can sustain only very low shearing stresses without flowing. Over long periods of time, during which the salt beds remain undisturbed by tectonic forces, the internal stresses in the salt will tend towards a hydrostatic condition in which the lateral stresses are equal to the vertical stresses and all stresses are equal to the superincumbent load (Serata, 1967).

The phenomenon of creep also presents a convenient means of measuring in situ stresses in the salt. Not only can rock stress changes be measured but absolute stress levels too. There are two main types of gauge which ought to be considered; these are hydraulic borehole gauges and photoelastic stressmeters.

Hydraulic borehole gauges.

One design of a borehole gauge is simply to pack off a section of a borehole, fill it with oil and connect the packed off section by a length of high pressure steel tubing to a pressure gauge situated at the mouth of the borehole (Baar, 1966). The borehole will tend to close under the influence of the stresses in the rock around it. As the borehole closes the oil pressure builds up in the packed off section and the pressure is recorded at the mouth of the borehole by a pressure gauge. Eventually the oil pressure reaches equilibrium with the stresses in the rock.

There is some difficulty in getting a pressure tight seal and it is more convenient to confine the fluid within a membrane.

Cylindrical pressure cell.

A type of hydraulic pressure cell can be made along the lines of the cylindrical pressure cell developed by the U.S.B.M. for the measurement of the in situ modulus of rigidity (Panek et al, 1964). The cell consists of a copper tube which is brazed at its two ends to an inner steel core. The space between the copper sheath and the steel core is connected to a high pressure steel tube. The cell is slid into a borehole and the copper sheath can be expanded by pumping fluid into the cell. The borehole should preferably be a diamond drill hole so that the walls of the borehole are smooth and the hole size should be only slightly greater than the diameter of the cell. If the hole diameter is not oversize the gauge can be inflated to pressures of up to 5000 psi. The cell can be installed in boreholes at considerable depth. For ease of installation the borehole should be drilled oversize for all but the last two feet. The cell should be installed immediately after drilling so that the hole will not close and prevent its insertion.

The main disadvantage of this type of gauge is that it reacts equally to stresses acting in all directions perpendicular to the borehole axis. This will give rise to complications when the stresses acting in the rock salt in a plane perpendicular to the borehole are unequal. In such cases the measured fluid pressures will lie somewhere in between the highest and lowest rock stresses.

Borehole flatjacks.

A borehole flatjack can be made quite easily by flattening a piece of soft copper tube (Skilton, 1968). The ends of the copper pipe are sealed using a silver solder whose melting point is around 1400°F. One end has a high pressure steel tube and a short filling tube leading through the seal. The gauge should be annhealed after fabrication by heating it to 1100°F for 8 hours. The annhealing ensures that the copper membrane will be able to expand a long way without splitting. The gauge can be filled with oil or glycerine and should be tested in a clamp to pressures of 4000 psi. The high pressure steel tube can be either 1/4 inch or 1/8 inch diameter. The large tubing has the virtue of being rigid enough so that the gauge can be pushed into the borehole using the tube. The smaller tubing requires the use of a setting rod for installing the flatjack, but it has great flexibility and can be coiled into a pigtail for ease of handling. Also the smaller tube contains a smaller volume of hydraulic oil which makes the entire system stiffer.

The flatjack can be installed in two ways. Either it can be grouted in place in the borehole or it can be encapsulated and then inflated to fit the borehole.

Grouting the flatjack in the borehole places less rigid requirements on borehole diameter. The process of grouting underground is time consuming and also time is lost waiting for the grout to cure before the cell can be pressurized. An alternative method is to encapsulate the flatjack in a cylinder of Lumnite mortar using a mould. The mould should be made from a tube the same diameter as the borehole but the mould is split into two halves, and the saw split is made 1/8th inch wide so that when the mould is put together the interior is not circular but flattened slightly. The flatjack is oriented inside the mould so that its plane coincides with the plane of the slit separating the two halves of the mould. The width of the flatjack should be about 1/8 to 1/4 inch less than the hole diameter. When the mortar encapsulation is hardened the mortar in the area near the edges of the flatjack is ground off to give the necessary borehole clearance. The encapsulated flatjacks are then lightly taped to prevent them splitting apart.

The encapsulated cells are installed in boreholes which are drilled oversize for all but the last two feet. When the cell has been slid into place inside the borehole it is inflated using a hand pump. A valve block is used at the outer end of the pressure tubing which provides a permanent connection between a pressure gauge and the flatjack and a temporary connection to the pump. The temporary pump connection is closed off after the flatjack has been pressurized.

In hard elastic rocks the pump up procedure can be used to provide a means of calibrating the hydraulic borehole cell so that observed fluid pressure changes can be related to rock stress changes (Sellers to be published). Fluid pressures will not change unless the rock stress changes. The sensitivity of the hydraulic system depends to a large extent upon the stiffness of the system. The stiffer the system the larger will be the observed fluid pressure changes for a given rock stress change. In order to make the system as stiff as possible it is necessary to minimize the fluid volumes used in the system and to ensure that the confines of the fluid are rigid. An ordinary Bourdon Tube type pressure gauge is a relatively 'soft' instrument in that it requires a relatively large volume change to actuate it. The pressure gauge can be made stiffer by substituting a photoelastic gauge for the Bourdon Tube type gauge. Figure 9 shows a typical encapsulated borehole flatjack and a photoelastic

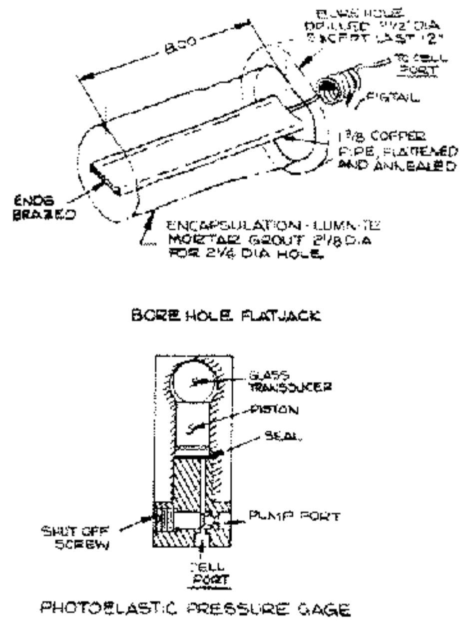

Figure 9. Hydraulic borehole gauge.

pressure gauge. The photoelastic pressure gauge has other advantages, one being that it is quite rugged and because of its shape can be pushed into the borehole out of harms way. (A pigtail on the 1/8th inch diameter pressure tubing will facilitate this procedure.) The photoelastic pressure gauge can have a range of about 3500 psi with an accuracy of around 40 psi. It is quite simply read by means of a small handviewer and cap lamp.

The borehole flatjack is quite insensitive to rock stress changes acting in a direction parallel to the plane of the flatjack. For this reason the flatjack reacts only to the rock stress changes in the direction perpendicular to the plane of the flatjack. For complete information on biaxial stresses, in the plane perpendicular to the borehole axis, it is necessary to encapsulate and install two flatjacks in the same borehole, one behind the other. Thus, for instance, one flatjack could be oriented to measure the vertical stresses in a pillar while another could be oriented to measure the lateral confinement stresses.

In a material such as rock salt the question of gauge stiffness is not too important because stresses in the salt cause any borehole to close. A flatjack grouted inside such a borehole would experience an increasing pressure which would cause an increase of fluid pressure inside the hydraulic system. Eventually the fluid pressure will build up to a level at which it is in equilibrium with the rock stresses. The stiffer the gauge the sooner the state of equilibrium is reached but the actual fluid pressure at equilibrium will not be affected by the stiffness.

Usually the borehole flatjack is pressurized to some pressure slightly greater than the estimated rock stress. The pressure will at first fall off as the grout encapsulation beds more firmly into the rock salt. Then as the salt continues to creep towards the hole the pressure in the flatjack will increase until equilibrium is reached, at which point creeping ceases and the fluid pressure remains constant.

From the theory of inclusions it can be shown that the stress inside an inclusion is close to 1.5 times the stress acting in the surrounding host material providing that the effective modulus of the inclusion is at least twice that of the surrounding material (Coutinho, 1949). The effect of creeping in a material is to lower its effective modulus, (Berry & Fairhurst, 1966) such that even inclusions with a lower effective modulus than the short term loading modulus of the host material will behave in a rigid fashion after the host material has undergone significant amounts of creeping. From this it can be stated that the fluid pressure observed in a borehole flatjack will eventually stabilize to a value approximately 1 1/2 times that of the stress acting in the rock in a direction perpendicular to the plane of the flatjack, providing that the octahedral shear strength of the rock is low.

The photoelastic stressmeter.

The photoelastic stressmeter (Roberts et al, 1965) has been used quite successfully in rocks and concrete for the measurement of stress changes. The stressmeter system is shown in Figure 10. The

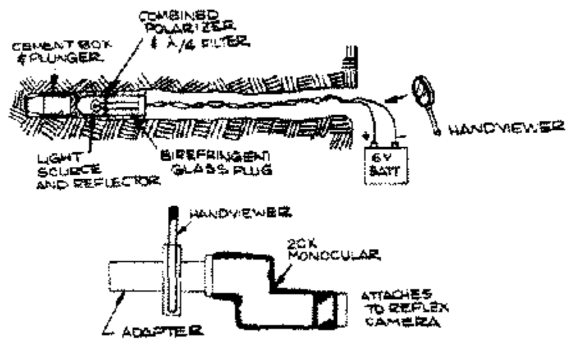

Figure 10. Photoelastic stressmeter.

glass transducer is grouted into a borehole using an epoxy cement. A polarized light source is arranged to shine through the glass transducer. Stresses in the glass give rise to interference fringes which can be viewed from the mouth of the borehole using a simple handviewer. At depths greater than 8 feet a telescope can be used. A reflex camera and color film can be used to obtain a photographic record. The stressmeter has been employed by the author to depths of 25 feet. The depth is limited only by the ability to see the gauge.

The advantages of the stressmeter are numerous. The gauge is accurate to around 30 psi; it is a biaxial gauge and records the total stress field in the plane perpendicular to the borehole axis; it is inexpensive, durable and rugged; there is nothing at the mouth of the borehole which can be damaged other than two electric wires which can be pushed back into the borehole out of harms way; the readout procedure uses a simple handviewer and 6 volt battery. Furthermore, when the stressmeter is used in rocks with a modulus less than 3×10^6 psi, the sensitivity of the gauge does not depend on the modulus of the rock. This statement is true also for rocks which exhibit creeping. In fact, in rocks which exhibit creep the stressmeter will measure the absolute stress level and it will do this simply by placing it inside a borehole in the rock and allowing the borehole to close down on the gauge (Hawkes, 1968).

Standard gauges have a 1 1/4 inch diameter for use in boreholes of around 1 3/8 inch diameter. For ease of installation the borehole should be drilled oversize for all but the last 18 inches. The stressmeter should be cemented in place as this will accelerate the time required for the salt to creep onto the gauge and set up the fringe patterns.

Stressmeter sensitivities depend on the length of the gauge. For a standard length of 1 1/2 inches the meter sensitivity in flowing rock salt would be close to 300 psi per fringe and the range would be 1500 psi. For added range to 4500 psi the gauge length would need to be 1/2 inch in which case the sensitivity would be around 800 psi per fringe and the accuracy would be about 50 psi.

ROCKBOLT LOAD CELLS

Rock mechanics instrumentation also has a part to play in measuring the effectiveness of rock bolt support systems. In soft rocks it is important to know what is the maximum anchorage capacity with each kind of rock anchor. Also it should be determined whether the rock bolt loads, under normal conditions, remain constant, diminish or increase. Maximum anchorage capacity can be conducted using a pull test which would eliminate unsuitable types of anchors. The remaining anchors which are acceptable on a short term basis should then be evaluated on the basis of their ability to hold their loads over long periods. For this purpose the bolts should be installed along with rock bolt load cells which can monitor the loads in the bolts from the time of their installation and thereafter. It is important that the rock bolt load cell be rigid so that any anchor slippage will result in the same loss of bolt tension that would occur in a bolt without a rock bolt load cell. Figure 11 shows two kinds of rock bolt load cells with electronic and photoelastic readouts. All load cells should have a cup and dome washer to apply loads evenly to the cells even though the bolt may not be perpendicular to the bearing surface.

The electronic type of rock bolt load cell is the most sensitive. One type, made by Terrametrics, uses a strain gauged steel cylinder, has an accuracy of ±100 lbs. This design will also permit a large degree of eccentric loading without appreciable loss of accuracy. The photoelastic type of rock bolt load cell made by Horstmann uses a thick wall

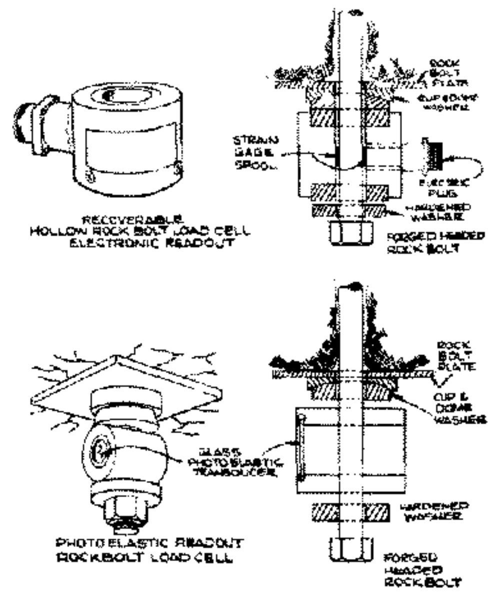

Figure 11. Rockbolt load cells.

steel cylinder which is loaded across a diameter. The deformation of the cylinder under loads is measured using a photoelastic glass transducer. This type of load cell is quite inexpensive, it has an accuracy of about ±250 lbs. It also has an advantage in that the readout device is a simple polarizing handviewer. Rock bolt load cells with mechanical readouts are also available. One type made by Interfels of Austria uses strong cup springs between an abutment plate and a yoke plate. Changing bolt loads cause small deflections of the cup springs and the movement of the yoke plate relative to the abutment plate it measures using a dial indicator. Another very simple device is the rock bolt load pad made by Goodyear; this consists of a circular rubber disc vulcanized between two circular steel plates. Changing loads in the bolt causes varying compression of the rubber pad, the circumference of which is measured by a special steel measuring tape. The accuracy of this latter type of load cell is around ±1 ton. Note that the mechanical readout load cells require considerable deflections in order for a reading to be made. The fact should be taken into account when estimating the behavior of bolts without such load cells.

INSTRUMENT APPLICATIONS

If the instrumentation program is to be successful the goals should be clearly defined. In the first instance the aim should be to investigate completely all the stress changes and deformations at enough locations that there can be a full understanding of the occurring phenomena. This will require a comprehensive array of instruments including multiple point borehole extensometers, borehole flatjacks, stressmeters, single point borehole extensometers, convergence rods and tape extensometer measurements. Using the information so obtained it will then be possible to design the instrumentation system so that the important movements and stress changes are monitored using the minimum of instrumentation suitably located.

Roof stability.

The question of roof stability revolves around the magnitudes of the side thrusts acting in the rock above the openings. Instability can arise from the side thrusts being either too large or too small.

If the lateral stresses above the opening are small then roof stability will be improved by keeping roof spans small. Where lateral stresses are low in one direction then the most stable configuration of a room and pillar mining layout will have long rooms separated by rib pillars with the long axis of the rooms oriented parallel to the direction of the minimum lateral stress. Crosscuts from one room to the next should be kept to minimum widths consistent with requirements for maneuvering the underground machinery. With this configuration of rooms and pillars the maximum available lateral stress is used to provide a clamping action in the rock beams over the mining rooms. Where lateral stresses are low the ever present danger is that of a roof fall where the unclamped roof simply drops out from beneath a weak bedding plane or joint plane. Often the edges of such a fall are also bounded by inherent planes of weakness.

Theoretically a pattern of 3/4 inch rockbolts on 4 foot centers should be able to suspend a rock beam of about 10 feet thick without any plastic yielding of the bolts. In practice the thickness of rock beam which can be suspended by such a bolt pattern is much less than this and will probably not be any greater than 4 ft. thick. This is because in the majority of roof bolting systems the installation procedures are erratic. Tensions on newly installed bolts may vary widely. Where bolts have been insufficiently torqued the anchorage may be poor. Failure of the anchorage after installation may cause some or all of the bolts to become loose. Failure of the rock around the rock bolt plate is also common especially where insufficient care is taken in positioning the rock bolt hole in an area of solid rock. All these factors mean that any tendency for the roof to fall from a plane of weakness intersected by the rockbolts, is resisted by only a portion of the bolts and it is possible that the bolts may be brought to failure not in unison but in succession.

In situations such as these the most significant improvements in the efficiency of the rockbolting system will be achieved by a rigorous enforcement of correct installation procedures. Efforts should be made to ensure that the best type of anchor is being used and that the anchorage does not deteriorate with time. Borehole extensometers at the center of the roof spans will detect and monitor the opening of cracks in the roof. Important road junctions should be instrumented in this way. Wide roof spans over important underground installations will require roof bolting using long, high-strength rock bolts. Here careful installation procedures, the use of rock bolt load cells and multiple point borehole extensometers should be mandatory.

The effect of temperature variations on roof stability can be profound. Most areas of a mine have a constant temperature but some areas close to the source of incoming fresh air can experience large temperature variations. Cold air entering the mine causes the rock around the airways to contract. The contraction in the rock beams spanning the roof can be serious. The shortening in length can reduce lateral stresses, which may already be dangerously low, so that their clamping or stabilizing effect on the roof beams is lost. The author has observed cyclic variations in the amount of roof sagging such that the roof sags measured in the coldest months were greater than those measured in the warmest months. Roof sagging occurred at its greatest rate during January and February. The maximum roof sags are measured in April after which the roof starts to move upwards at its fastest rate during the months of July and August. The roof reaches its highest position during the month of October. In the same mine, which had very low lateral stresses in one direction, there had been a few major roof falls in unfavorably oriented roadways, that is oriented at right angles to the direction of the low lateral stresses. All of the roof falls occurred during the winter months.

In deep salt mines the main problem of roof stability will be that of high lateral thrusts causing the immediate roof to buckle downwards. Similar stresses in the floor will give rise to floor heaving. The lateral stresses giving rise to these phenomena can be measured using borehole flatjacks and stressmeters in the roof and floor. Multiple Point Borehole Extensometers and Single Point Borehole Extensometers will help to locate the thickness and numbers of the deforming beds. They will also measure the magnitude of the deformations and monitor the extent to which rock bolting can prevent or retard the roof buckling. (Floor heaving might also be reduced by floor bolting.) A condition of instability in a roof can be inferred from accelerating deformations as measured by extensometers. Accelerations may require at least a temporary abandonment of the area or require the installation of additional support in the form of rock bolts or posts.

Pillar stability.

Pillar stability will depend on the magnitude of the shearing stresses in the pillar, relative to the shearing strength of the rock mass. In its natural state the rock salt will most probably be subjected to almost hydrostatic conditions, because any differential stresses, giving rise to shear stresses, will have been removed by plastic flowing over long periods of time. When a pillar is formed underground the lateral stresses in the pillar are removed leaving only the vertical stresses (assuming a flat lying salt bed). The high shearing forces so produced cause a rapid diminuation of pillar height accompanied by a general lowering or subsidence of the rock above the pillar. The shortening of the pillar height occurs simultaneously with the dilation of the pillar. This sideways extrusion of the pillar is resisted by internal friction or the salt's viscosity. The resistance gives rise to the growth of horizontal stresses in the pillar. These 'confining' stresses increase towards the center of the pillar, they reduce the shearing stresses and slow down the rate of pillar convergence. Eventually a state of equilibrium is reached at which the pillar converges at a uniform rate. This uniform rate will depend to a great extent upon the size of the pillar. The larger the pillar the less the final rate of convergence will be. In a small pillar there will be little confinement so that the final rate of convergence will remain large.

Where pillar sizes are uniform the creeping of the salt in the pillars will result in a uniform lowering of the rock strata above the salt beds being mined. But if there are large pillars and small pillars the smaller pillars will try to converge at a faster rate than the larger pillars. This will result in the gradual transference of the superincumbent load to the larger pillars. The vertical loads in the smaller pillars will diminish and so will the shear stresses and convergence rates until once again the entire zone is subsiding at a uniform rate. In this situation, however, there will be large distressed zones existing in the strata, above and below the smaller pillars. These distressed zones then serve as a sink into which groundwater or gases will flow. Such accumulation of water and gas close to the underground opening would be a serious hazard. Again if the build up of stresses in the larger pillars occurs at a faster rate than can be dissipated by faster rates of pillar convergence then there would be a danger of very high pillar stresses and the salt failing in a brittle fashion in the form of a rockburst.

On the basis of the preceding analysis it is possible to see that the best mine design would be one which allows a uniform or gradually changing rate of pillar shortening throughout the mine, plus a uniform distribution of pillar loading. Sudden changes in pillar size and percentage extraction ratios should be avoided. The boundaries of the mine openings should not terminate abruptly but should be phased out in the form of a gradual reduction in the percentage extraction ratio. Main access roadways should not be protected by barrier pillars on either side but by additional roof bolting pillar bolting and extra maintenance as required.

Percentage extraction ratios should be so chosen that the rate of pillar closure is acceptable in terms of the length of time that the openings are required to be used. Pillar sizes should be designed to be as large as possible so that for a given extraction ratio the convergence rate will be a minimum. The maximum pillar size will be limited by the maximum stable width of the openings which will have to be wide in order that the required extraction ratio can be obtained.

From the foregoing it should be apparent that pillar stability is not fully determined by measurements of pillar convergence of pillar dilation alone but also requires a measurement of pillar loading. Mine wide measurements will show anomalously stressed areas which may require the partial mining of certain barrier pillars or boundary pillars, or the creation of additional support in some areas perhaps by the use of larger pillars near some geological disturbance or by filling some abandoned roadways with waste fine salt products.

Borehole flatjacks or stressmeters in or near the center of a pillar will measure pillar stresses in both vertical and horizontal directions. A stable condition will be shown by constant stress levels while unstable conditions will be revealed by either rising or falling stress levels, which can be interpreted in the light of measurements of pillar convergence and dilation in the surrounding area.

Brine well cavities.

Another application of instrumentation which is of interest to the salt mining industry is the measurement of ground movements above brine well cavities. Figure 12 shows the use of multiple point borehole extensometers for the measurement of subsidence above a brine cavity. As the cavity

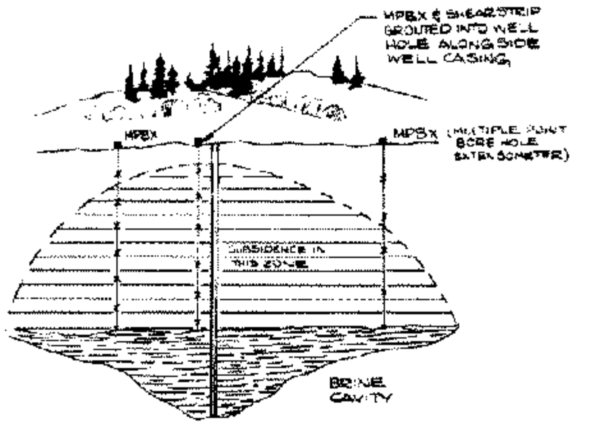

Figure 12. Instrumentation of a brine cavity.

grows in size, the ground above it will subside and the zone of subsidence will enlarge. The extent of the zone of subsidence can be measured on the MPBX's and the approach of the subsidence zone to the surface can be monitored and if necessary the pumping discontinued at some time in order not to disturb the surface. Also shown in the figure is a Terrametric's Shear Strip which is a device for detecting the position of any underground fracturing occasioned by tension or shear failures. It consists of two parallel printed circuit conductors bonded to a frangible strip. The two conductors are connected at intervals by resistors in parallel. A break in the circuit alters its electrical characteristics. This device can be grouted into the well bore along side the well casing.

CONCLUSIONS

Simple instrumentation techniques exist for monitoring the stability of underground salt mines. If properly used these techniques will enable the extraction ratio to be maximized without compromising safety. They can also be used to diagnose existing problems of instability and monitor the effectiveness of any corrective measures taken.

These benefits can only be realized in proportion to the thoughtfulness and completeness with which the necessary instrument stations are located and the care with which the measuring instruments are installed and the measurements made, processed and interpreted.

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