Methods and Equipment for Measuring Subsidence

Louis A. Panek
Research Manager, Ground Control Technology
Bureau of Mines, U.S. Department of the Interior
Denver, Colorado

ABSTRACT

Subsidence of the earth's surface is the inevitable result of extracting a substantial volume of mineral material from beneath the surface. The subsidence profile has the general shape of a basin, along which any given point may be displaced both vertically and horizontally. Since the displacement is not the same for all points, surface structures may be subjected to differential settlement, tilt, and horizontal deformation. The amount and distribution of these distortional phenomena depend on the geometry of the extraction zone and on the structural characteristics of the undermined rock strata.

Both analytical and experimental approaches have contributed to our understanding of subsidence mechanics. Only actual field measurement, however, can provide numerical values for the important parameters, knowledge of which is prerequisite to rational design and control.

Experience indicates that any company engaged in extracting minerals from the earth should conduct at least a token program of subsidence measurements. This report describes measurement techniques and equipment that are appropriate for determining the horizontal and vertical components of displacement and strain, tilt and curvature. Particular attention is given to the principal characteristics and uses of monuments, extensometers, tapes, electronic distance-measuring instruments, theodolite, alignment telescope, spirit level, tilt meter, and borehole inclinometer probe. Choice of an appropriate combination of elements with which to carry out a subsidence study depends on the type of information sought, the precision required, the funds available for making the initial investment in the instruments and permanent field markers, and the manpower available for performing the measurements and reducing the data.

INTRODUCTION

The ultimate objective of measuring subsidence is to develop a rational basis for predicting the magnitudes and locations of the significant subsidence components that occur as a consequence of subsurface mineral extraction. Predictive capability is in turn the basis for devising an extraction sequence that will control or restrict surface subsidence, so as to avoid damage to surface structures or facilities. Or, if damage is already visible, one may wish to evaluate the situation by predicting the future course of subsidence, corresponding to various alternatives such as continuation of the extraction operation, cessation or modification.

Accurate prediction or evaluation of subsidence components requires measurement of these components for a range of values of the parameters that specify the extraction geometry and the geological structure. If the geological setting is essentially the same for all extraction operations that are to be considered, then the prediction can be based on the depth, size, and shape of the extraction volume; this approach has been successful for coal mining in the U.K.

However, if the structural characteristics of the overburden are significantly different, as between one geographic area and another, then a mathematical model is a very useful device for incorporating relationships that are derived by structural analysis. Formulation of a realistic mathematical model of the structure requires that the structural parameters (bed thickness, deformation modulus, etc.) be specified and the deformational behavior measured. These are two definite reasons for making field measurements and observations.

The measurement of subsidence is essentially a problem of applied geometry. The purpose of this report is to enumerate measurement techniques that are available, the subsidence components that can be determined by each method, and the measurement precision that is ordinarily achieved. In order to provide a better understanding of the reasons for measuring the various components of subsidence, a review of the essential characteristics of subsidence precedes the discussion of measurement techniques.

SUBSIDENCE CHARACTERISTICS

Subsurface extraction of a mineral material creates a void, which results in a lowering of the earth's surface above the void, Figure 1. Measurements show that the affected surface area or subsidence basin exceeds the area of extraction, even though this may not be apparent to the eye. The "angle of draw" from the extraction boundary to the outer limit of surface subsidence may be as much as 45° from the vertical, depending on the structural characteristics of the rock strata overlying the area of extraction. It is obviously difficult, even by highly precise methods of measurement, to detect where the asymptotic subsidence curve reaches exactly zero vertical displacement. The angle of draw determined by other than a precise surveying method is much less than the true value. Some observers have reported angle of draw values based on visual observations, which more likely correspond to the outer limit of surface cracking, or to the boundary of an obvious slump zone.

Subsidence may consist of a gradual downwarping of the surface, or it may progress to the stage where large blocks slump in stair-step fashion. The intensity of the surface disturbance depends on the thickness of the overlying rock strata and the height of the void that is created. One would not be surprised by a cave-in following removal of a 5-ft thick layer with only 6 ft of cover above it, whereas experience shows that mining out a 5-ft seam of coal under 600 ft of cover ordinarily causes no more surface disturbance than a gradual settling of about 4 ft. The diameter or span of the void is also significant, because a 500-ft-high void clearly will not result in caving of the overlying strata if its diameter is only 5 ft.

Many measurements made above coal mines in the coal fields of the U.K. (National Coal Board,

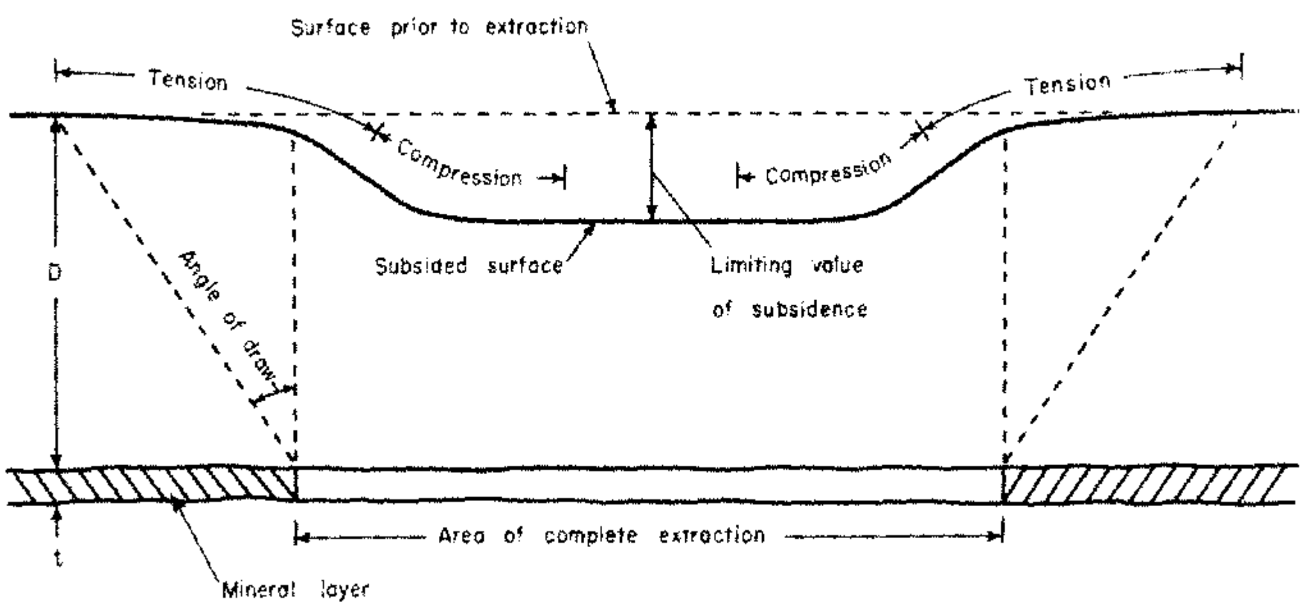

Figure 1. Subsidence characteristics.

1966) reveal that the limiting value of subsidence is reached when the span of the void (the area of complete extraction) exceeds 1.4 (D = depth) and that the limiting subsidence amounts to about 0.9t (t = seam thickness). The depth of the subsidence basin can be reduced by decreasing the span of the void. Above these coal mines, for example, the maximum subsidence is only about 0.45t if the span of the void is about 0.7D.

Any surface subsidence basin (Fig. 1) consists in general of an outer belt or zone of horizontal tensile strain, surrounding an inner zone of horizontal compressive strain. If the span of the underground void is great enough (1.4D for a 5 ft seam) to produce the limiting value of surface subsidence in the center of the subsidence basin, then this comprises a third (and lowest) zone, in which there is no horizontal strain. In other words, the tension zone and the compression zone together comprise a disturbed zone of transition between the central relieved but fully subsided zone (if the subsidence basin is fully developed) and the as yet undisturbed ground surface surrounding the subsidence basin.

As the subsidence basin grows in area, owing to the progressing extraction, more and more surface structures in effect enter and pass through the disturbed transition zone, where they are subjected first to a stretching and then to a compressing. Considering the profile of the subsidence curve, Figure 1, it can be seen that while the surface structure is in the tension zone it is also subjected to an increasing tilt, due to the slope of the ground surface, and to an upward "bowing" or flexing, due to the curvature of the ground surface; in the compression zone a surface structure is subjected to a reverse flexing with decreasing tilt.

In order to evaluate the effects of surface subsidence, therefore, one must consider not only the effect of the vertical displacement, which is the most obvious characteristic of subsidence, but also the effects of horizontal strain, tilt, and curvature. These components of displacement and distortion are illustrated in Figure 2.

Vertical displacement will not of itself damage a surface structure, provided the displacement varies more or less uniformly along the profile, without excessive settlement of one part of a building relative to another. Vertical displacement will, however, alter the drainage, the rainfall runoff, the flow of creeks, and the gravity flow of liquids in pipelines, such as water and sewer lines; and it will alter the grade of a highway or a railroad bed.

Horizontal strain can cause distortion, cracking and failure of buildings (National Coal Board, 1966; Sinclair, 1963), pipelines (Tilton, 1966), highways (National Coal Board, 1966), and railroad rails (Rellensmann, 1957). The National Coal Board found the degree of damage to be so dependent on the nature of the structure that only approximate rules can be formulated for predicting the severity of damage (National Coal Board, 1966; Wardell, 1969). The main factors are the intensity of horizontal strain and the size of the structure; damage was very slight or negligible for a strain less than 1000×10^{-6} and a structure less than 100 ft long. The maximum value of tensile horizontal strain occurs at or slightly outside the extraction boundary, the maximum compressive strain inside the boundary. For coal mining, the magnitudes of these maxima are proportional to the depth of the subsidence basin. The National Coal Board found upper limits of about (2/3) (S/D) for these maximum horizontal strains (S = limiting value of subsidence, D = depth below surface) (National Coal Board, 1966).

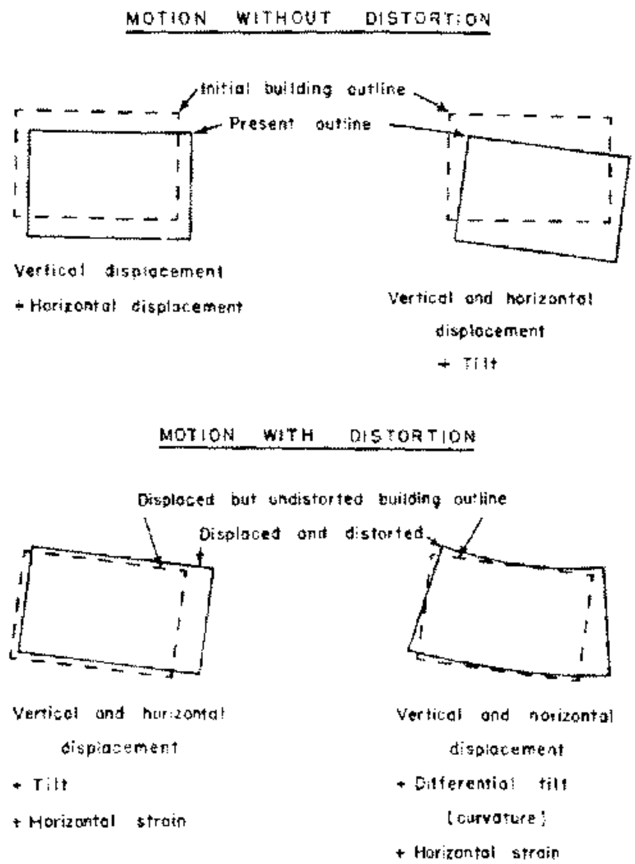

Figure 2. Components of displacement and distortion, illustrated by their effects on a surface structure.

Inclination or tilt of the ground surface can result in instability of a tall structure such as a smokestack; it can cause malfunctioning of machines, cranes or elevators; and it can cause overflowing of a tank or interfere with gravity drainage of waste from a building.

Curvature of the ground surface (Fig. 2) can cause flexure of a building, which may have results very similar to those caused by horizontal strain. The taller the structure the greater the distortion due to curvature.

It is interesting to observe that if a structure is not "anchored" to the ground, all types of subsidence disturbance, except tilt, may be averted. For this reason the National Coal Board recommends that buildings erected in subsidence areas should be designed to be either completely flexible or completely rigid (National Coal Board, 1966). Hurst, Owen, and Bayrac (1966) have given an interesting account of the deformation behavior of a specially designed three-story school building subjected to subsidence.

PREDICTING SUBSIDENCE COMPONENTS

In order to "live with" subsidence, or control its location, or limit its magnitude, one must be able to estimate or predict the numerical values of maximum vertical displacement, maximum horizontal strain, maximum tilt, and maximum curvature for a given depth, thickness, length, and width of extraction volume; one must be able to draw contour lines over the extraction area to indicate the expected amounts of vertical displacement, horizontal strain, tilt, and curvature at any location in the subsidence basin and for any stage of extraction.

British and European experience show that remarkably consistent relations can be found among the geometric parameters (depth, width, thickness, span of the void) and the significant subsidence variables (displacement, tilt, strain, curvature). It is not to be expected that the numerical values found in one region will hold true in another, where different strata overlie the extracted layer, nor that the numerical values will be the same for a 5-ft coal seam as for a 15-ft salt bed. The point is, however, that one *can* expect to find consistent relationships if one makes measurements of actual subsidence behavior.

Armed with this information one will be in a position to decide, for example, the relative merits of completely extracting a mineral bed over a wide area versus distributing the total extraction area to a number of separate, narrow subareas. The first procedure will yield the greatest mineral recovery per acre; the largest part of the subsidence zone will experience the maximum vertical subsidence but should be free of horizontal strain, tilt, or curvature; the maximum values of these components will be relatively large but will be localized along the perimeter of the extraction zone. With partial extraction, the second procedure, it has been found possible (Wardell, 1969) to arrange the shape, size, and spacing of panels and pillars so as to reduce subsidence to a fraction of the limiting value. Experiments have been made in Europe and the U.K. (Fritsche, 1954; Sinclair, 1963, Wardell, 1957), to completely extract a seam by a sequence of panels, in such a way that a critical building remains always in a relatively favorable position with respect to horizontal strain.

Theoretical analyses have been made by many authors to describe the structural behavior of the overburden by the classical methods of theoretical elasticity, viscoelasticity and plasticity, by soil mechanics principles, and by treating subsidence as the stochastic (probability) motion of particles in a granular medium. These approaches have contributed to our understanding of the mechanics of subsidence and are capable of describing subsidence behavior in a general way, but they have not been successful in predicting the actual numerical values of the subsidence components. This is partly due to the inherent limitations of the methods of analysis, which can only handle overly simplified structural models, and partly because we have not yet learned how to quantify all the significant parameters of the geological structure.

In the Bureau of Mines we are pursuing both approaches, theoretical analysis and field measurement. That is, we believe that the most effective procedure for predicting subsidence is through the use of a valid mathematical model of the overburden structure, because a structural model can make the best use of subsidence measurements that may be available, from the district of interest or from another geologically similar district. We further believe that subsurface investigations of the overburden structure are necessary to the development of a practical mathematical model.

Consequently, we are using the finite element method of structural analysis to model the behavior of more complex overburden structures than has been attempted heretofore, taking into account a number of separate rock strata, orthotropic rock properties, nonlinear stress-strain behavior, time-dependent deformations, and an arbitrary configuration of the extraction area. The mathematical model will be refined by comparing predicted subsidence components with the values found by field measurement.

We are conducting studies of the subsurface behavior of the rock structure overlying an extraction area. Although surface subsidence has been measured in many countries, subsurface measurements have received scant attention. Yet surface subsidence phenomena comprise the behavior of only one boundary of the large mass of strata overlying the extracted mineral seam. Formulation of a valid mathematical model of this structure requires quantitative data to specify the structural properties of the strata, primarily their deformation moduli, strengths, densities, and thicknesses, and the spacing and attitude of joints and fractures. We must also describe the structural behavior by measurements of displacements, deformations, strains, and stresses.

Systematic progress can be achieved by beginning *now* to conduct a program of actual field measurement of displacements, strains, and tilts. It must be recognized that subsurface data cannot be obtained more rapidly than extraction progresses; it is impossible to make up for lost time. The writer too often has participated in a fruitless discussion following some indication of significant ground movement observed by a miner (no actual measurement available), and was unable to develop answers to questions such as; How much movement occurred? Did it occur during a period of stability, or was it preceded by a period of increasing activity? What is the present rate of activity (inactive, steadily increasing, or falling off)? A ground-movement monitoring system cannot be installed over night, with the best of intentions. By the time it is operating, the ground may have returned to equilibrium, and hence, no real information is obtained. Even worse, there is no explanation of what actually happened, which would be the basis for instituting measures to prevent recurrence. Any company will find it well worth the expense, as a form of insurance against unpleasant ground movement surprises, to maintain some form of continuing subsidence surveillance throughout the period of extraction. When a sudden change occurs, by far the most useful information, from which to form an opinion as to the present status and future developments, is the past trend of displacement, strain, or tilt measured at selected points above the extraction area.

MEASUREMENT OF SUBSIDENCE

A program of subsidence measurement begins with the installation of monuments, casing, or other permanent hardware that will be undisturbed by temperature, frost, animals, etc., and that will reflect only the displacements of the underlying rock. The first survey should be completed before extraction begins, or there will be difficulties in the interpretation of the data. Measurements of distances, angles, and inclinations are repeated at intervals during extraction, making use of various mechanical, optical, and electronic devices.

The number and frequency of surveys depends on the extraction volume and area and on the objectives of the subsidence study. For extraction of a 300-ft wide panel in a 6-ft seam with 600 ft of cover, a 2-month period of observations may be sufficient to yield all the desired information; observations may be made daily during the most active period and less frequently at other times. For extraction of a 200-ft thickness of ore at a depth of 1000 ft or more, observations ordinarily will be continued for several years, with two to four surveys per year, except during the year of most rapid subsidence activity when monthly or bimonthly surveys may be desirable.

Uncertainties will be introduced into the data by the use of any element of the measurement system that is affected by moisture or by changes in temperature, illumination, or barometric pressure. These environmental factors are quite severe in their influence on precise measurements that must have stability and repeatability over a period of several years.

For a subsidence study in the northern U.S. preference should be given to carrying out the measurements in the spring and/or fall, in order to avoid temperature extremes. If the surveyor resides within commuting distance he should try to restrict his measuring activities to cloudy days; the improvement in his data will be significant. Activities that require continuous mental concentration, such as observing by theodolite or precise leveling, should be limited to about 4 hours per day.

A surface subsidence study ordinarily requires two distinct sets of measurements, which usually are done with different instruments, one set to detect motion in a horizontal plane and one to detect motion in a vertical plane (King and Jones, 1956). Methods and instruments for making these two types of measurements will be discussed following a brief summary of some considerations relating to subsidence monuments.

Monuments.

For convenience in the present discussion the term "subsidence monument" denotes any type of marker, irrespective of its permanence or rigidity, which is placed in the area of expected subsidence; that is, a subsidence monument is expected to experience vertical or horizontal displacement or tilt. The term "observation point" denotes a permanent type of monument or instrument support (Fig. 3), which is placed outside the area of expected subsidence, in order to remain free of displacement or tilt.

In order to facilitate analysis of the data, subsidence monuments should, if possible, be placed along profiles that are parallel to and perpendicular to the direction of advance of a mining panel, or along several profiles radiating from the center of an extraction area such as a brine well.

The appropriate spacing between adjacent subsidence monuments depends on the gradient, along the profile, of the subsidence components (usually strain or tilt) that are of primary interest. Putting the monuments too close to each other increases the cost of installation and subsequent measuring. Monuments that are too widely separated fail to properly "sample" the distribution of the measured variable and lead to measurements that are in effect averages of high and low values. Based on practical experience, the National Coal Board (1966) recommends a spacing of D/20 (D = depth).

Monuments are sometimes placed in a rosette configuration (Fig. 8) in order to provide for subsequent calculation of the direction and magnitude of maximum horizontal strain. Similarly, a rosette pattern may be employed for tiltmeter supports on a single monument (Fig. 6).

If the relative motion of two points on the earth's surface is to be determined with precision, the motion of an individual point must be

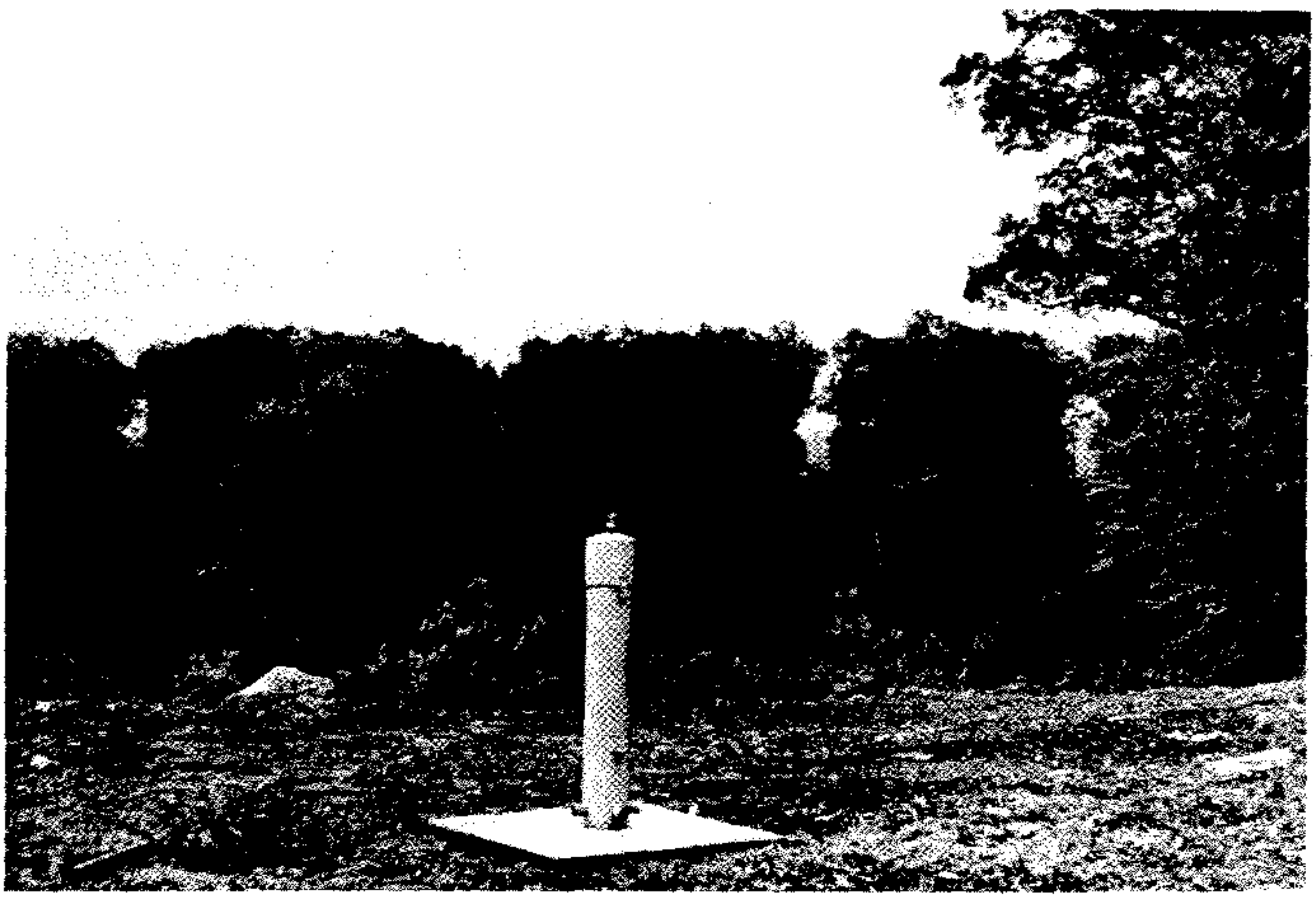

Figure 3. Observation point. Serves as fixed reference point when protective cover and theodolite target are in position as shown. Cover and target are removed in order to mount theodolite.

unaffected by humidity, water, air temperature, direct sunlight, or frost heave.

Tilt of the monument should not falsely influence the measurement of distance between the monuments, or provision should be made to apply appropriate corrections to the measurements. Tilt due to rotation of the monument away from the normal to the profile constitutes a spurious behavior, as it does not represent inclination of the profile. The effect of spurious tilt is minimized by keeping the points of measurement on the monuments close to the ground.

Steel rods driven 2 to 3 ft into the ground have exhibited unexplained movements, horizontal as well as vertical, thought to be due to frost heave. Achieving stability of monuments is complicated in some areas by the presence of swelling clays in the soil.

A stable monument for the northern U.S. climate may be constructed by excavating a 1-ft-diameter hole 4 to 5 ft deep with a post-hole digger, filling the hole with concrete and setting one or more "measuring points" into the concrete. The measuring points may consist of steel rods or screws that will later serve to mount a triangulation target or tilt meter, or to support a leveling rod or a taping connector.

SURFACE MOTION IN A HORIZONTAL PLANE

The most important parameter of horizontal motion with respect to the disturbance of surface structures is the horizontal strain, which is the change in length of a line segment, expressed as a fraction of its initial length. Horizontal strains can be determined within a small area without regard for the shift of the area as a whole, but usually one wishes also to know how much the area has been displaced with respect to some fixed point. Another reason for determination of horizontal displacements may be that this provides an appropriate means of deriving the horizontal strains, for example because one already has the measuring instrument available or because the area will later be inaccessible for safety reasons. Both horizontal strain and horizontal displacement are therefore of interest and they are usually interconvertible, one to the other. The discussion that follows is directed primarily to the determination of horizontal strain, because this usually has greater immediate significance.

Horizontal strain can be obtained either by repeated direct measurement of the horizontal distance between adjacent subsidence monuments or from repeated determinations of the positions of subsidence monuments with respect to a fixed reference point, such as an observation point. The determination of length, which is involved in both approaches, can ordinarily be done to a precision of the order of 10 parts per million without unusual difficulty.

Direct measurement of distance.

The procedure consists of making repeated direct measurement, over a period of time, of the distance from any subsidence monument to the adjacent subsidence monument. The average horizontal unit strain is calculated from

$$\text{Horiz. strain, Mon. 1 to Mon. 2} = \frac{\text{Change in horiz. distance, Mon. 1 to Mon. 2}}{\text{Initial horiz. distance, Mon. 1 to Mon. 2}} \quad (1)$$

For direct measurement of length an extensometer is appropriate for short distances, a tape for medium distances, and an electronic distance-measuring instrument for long distances. The lengths to be measured will, in most instances, range from about 10 ft to about 2000 ft.

The most severe sensitivity requirement with respect to measurement of length will occur in attempting to detect the minimum increment of unit strain by measurement over the shortest length. Based on the National Coal Board recommendation that the spacing of subsidence monuments be no greater than D/20 (D = depth), in order to avoid the "dilution" of the largest unit strain values, and assuming that the mineral seam will be at a depth of at least 200 ft, then 10 ft is the shortest "gage length" that need be considered. If the minimum unit strain to be detected is taken to be 100×10^{-6}, about one-tenth the strain level for structural damage, then one must be able to measure a 10-ft length to within about 0.010 inch.

For measurement of a 10 to 20-ft length with a sensitivity of 0.010 to 0.020 inch, one can appropriately employ an extensometer or deformeter, consisting of a rod or tube on the end of which is mounted a dial gage, (King and Jones, 1956) a graduated scale, or a linear potentiometer. An ordinary machinist's scale graduated to 1/50 inch can be read to 1/100 inch. Use of a potentiometer would permit telemetering and recording, should this be desirable.

Decreasing the extensometer length to 6 or 8 ft might improve the convenience of handling and transporting it (at the expense of an increased number of subsidence monuments, if there is no reduction in the area to be monitored), but there is no point in further reducing its length because the sensitivity requirement will rapidly become excessive, considering the inexpensive and reliable measurements that can be achieved by a vernier scale or a dial gage.

Correction for temperature changes will be a problem unless the extensometer rod is made of invar or a similar alloy.

If the number of subsidence monuments is small, consideration can be given to permanently placing a measuring device between each pair of monuments. Increasing numbers of monuments favors the use of a single extensometer which can be moved in succession from one pair of monuments to the next.

For distances greater than 10 or 20 ft, the weight of the measuring device and the convenience of transporting and handling it favor the use of a one-piece metal band, tape or wire, probably the simplest and most direct method for measuring length. Standard surveying practice for high-precision taping is required, proper attention being given to temperature, tensioning, sag, inclination and reading of the tape.

In measuring with a metal band, a tape, or a wire, just as is true with an extensometer, temperature differences will increase the scatter of the data unless the tape is made of invar or a similar alloy having a low temperature-coefficient of expansion, because evaluating the effective tape temperature, in order to make a temperature correction, is a practical impossibility under ordinary conditions of use.

Consistent length measurements require that the tape be stretched to a constant tension, ordinarily 10-30 lb, while the measurement reading is being taken. This may be achieved by applying a pull to the tape through a spring balance or by connecting the tape to a weight suspended over a pulley. A change of about 3 lb tension can alter the length of a 100-ft tape by 0.001-0.002 ft, depending on its cross-sectional area.

Even with constant tension, the indicated measurement depends on the amount of sag that occurs in the tape over the distance of measurement. The error in indicated length is 0.01-0.04 ft for a 100-ft-long unsupported tape tensioned to 30 lb, 0.009-0.37 ft at 10 lb tension, depending on cross-sectional area (Davis, Foote and Rayner, 1934). The only reliable approach is to support the tape, either continuously or at short intervals between the points of measurement.

If the inclination is not large, the horizontal strain will not be substantially influenced by the fact that the tape is not truly horizontal when the measurement is taken. Since the objective is to detect *change* of distance, the essential requirement is to follow a standard procedure such that the tape is held against the same point on the subsidence monument for each repetition of a given distance measurement.

A typical surveyor's tape has graduations at 1-ft intervals, except for the last foot, which carries 0.01-ft graduations. Distance is measured by holding a 1-ft graduation to coincide with the index mark on one subsidence monument, while observing the nearest 0.01-ft graduation opposite the index mark on the other subsidence monument. More sensitivity is obtained by employing an auxiliary graduated scale 6 inches or less in length (such as a machinist's scale) to measure the distance from the index mark on the subsidence monument to any convenient graduation mark on the tape. The auxiliary scale should be graduated at intervals of 1/50 inch, so that the "fine reading" can be observed to the nearest 1/2 division, 0.01 inch, which is about the smallest increment that can be conveniently distinguished with the unaided eye. Use of a vernier to increase the sensitivity of the reading is not recommended because the measurement accuracy will not justify the additional time expended except where the taping is done under very closely controlled conditions (uniform temperature, tape supported throughout its length, etc.).

If subsidence monuments intended for taping measurements are placed very nearly at equal distances from each other, so that the index marks are equally spaced to within about 0.01 ft, which is not difficult, then the invar band, tape or wire need have only two index marks, one at each end. In this case, the distance between subsidence monuments is measured by holding one tape index mark to coincide with the index mark on the first subsidence monument, while using the auxiliary scale to measure the distance from the other tape index mark to the index mark on the second subsidence monument.

Taping measurements can be performed by one man if the subsidence monuments and one tape-end are constructed so that the tape can be attached to one monument while the distance reading is being taken (and the tape tensioned) at the other monument. This procedure requires monuments that are rigid enough to withstand 30-lb tape tension with a deflection less than the smallest reading scale graduation. If the monuments are too lightly constructed to permit this, then, while the reading is being observed at one end of the tape, a second man will be required at the other end, to maintain coincidence of the tape index mark with the monument index mark.

Taping by one of the foregoing procedures ceases to be practical for distances greater than 100 to 200 ft, which are moreover too great for determination of meaningful horizontal strain values, considering the D/20 maximum recommended spacing. For lengths of this magnitude one is in effect limited to consideration of horizontal displacement or horizontal control of the survey.

Direct measurement of distances greater than 100 to 200 ft can be done by one of the electronic distance-measuring instruments that have become commercially available in recent years. An instrument of this type, positioned at a subsidence monument or an observation point, emits a light beam or a radio beam. At the adjacent subsidence monument the beam is received by a second instrument or is reflected back and received by the transmitter. The instrument compares the phase of the transmitted wave to that of the received wave, thus obtaining a measurement of distance in terms of a fractional wave length. An instrument error of about 0.05 to 0.10 ft, independent of the distance measured, is characteristic of these instruments, which are not intended for measuring the relatively short distances involved in subsidence studies. In addition there is a variable error due to changes in temperature, pressure, and humidity, because these factors affect the index of refraction of the atmosphere and therefore the wave velocity.

By employing special procedures such as measuring the apparent distance between a pair of targets separated by a fixed distance (e.g., 8 inches) and mounted on the subsidence monument, and using this value as an in-place calibration, the constant instrument error can be largely eliminated and about 0.005-ft precision of measurement achieved. When a technique of this type is employed, an electronic distance-measuring instrument becomes competitive with taping for determination of horizontal strains over shorter distances.

An electronic distance-measuring instrument measures the slope distance rather than the horizontal distance between points, and hence the latter must be calculated from

$$\text{horizontal distance} = (\text{measured slope distance}) \cdot (\cos i), \qquad (2)$$

where i is the angle of inclination, above or below the horizontal, from the transmitting instrument to the subsidence monument, an additional instrument and procedure must be employed to determine i, either (1) measuring i directly with a theodolite or (2) measuring the vertical distance between the two points by differential leveling, both of which are described in the next section.

An electronic distance-measuring instrument has an advantage in hot weather, because it is convenient to use at night, when atmospheric problems are a minimum.

Position determinations by intersection.

The procedure consists of making repeated determinations, for each subsidence monument, of its position in a horizontal plane. The displacements of a monument are the successive changes of its calculated position. The average horizontal unit strain between any two adjacent subsidence monuments is calculated from

$$\text{Horiz. strain, Mon. 1 to Mon. 2} = \frac{(\text{Horiz. displacement Mon. 2})-(\text{Horiz. displacement Mon. 1})}{\text{Initial horiz. distance, Mon. 1 to Mon. 2}} \qquad (3)$$

The intersection method, which may be used to determine the position of a subsidence monument, ordinarily consists of measuring horizontal angles with a theodolite and calculating the monument position from trigonometric relationships. Actually each monument must be observed separately from two observation points, which are ordinarily several hundred feet apart. The distance between the two observation points must be known, but not to high precision. Each subsidence monument thus forms the vertex of a triangle in which the base line is of known length. The angle at each end of the base line is measured by a theodolite that has a sensitivity on the order of 1/2 second of arc. The distance to the subsidence monument is calculated from the law of sines. A precision of about ±0.01 ft can ordinarily be achieved by this method, for monuments 800 to 2,000 ft from the observation points.

The essentials of the intersection method are illustrated by Figure 4. The subsidence monument at M is observed from the two observation points A and B, in order to measure the angles A and B. Now,

$$\text{angle M} = 180^\circ - (\text{angle A}) - (\text{angle B}). \qquad (4)$$

Applying the law of sines, the length of a can be calculated from

$$\frac{\sin A}{\text{length a}} = \frac{\sin M}{\text{baseline length}} \qquad (5)$$

The azimuth or bearing of the monument from point B is obtained from the bearing of the base

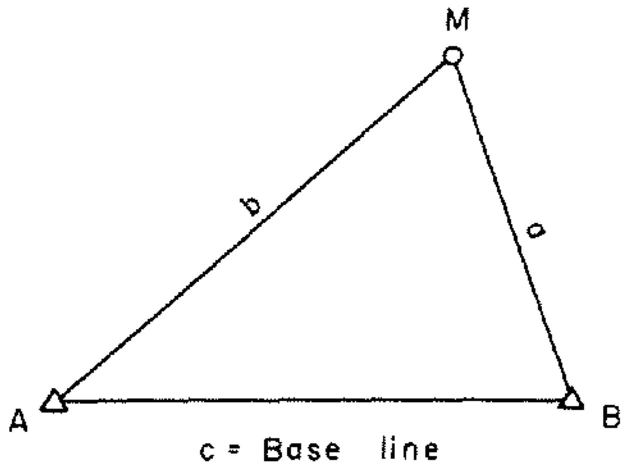

Figure 4. Intersection method.

line and the measured angle B. The coordinates of M are calculated from those of B, using the length and bearing of *a*.

As will now be shown, the baseline length need not be determined to high precision, a very tedious and time consuming task that must be done in geodetic surveying. Let us suppose that

$$\text{assumed baseline length} = 0.99 \times (\text{true baseline length}).$$

Then, from eq 5, it can be seen that

$$\text{calculated length } a_o = 0.99 \times (\text{true length } a_o), \tag{6}$$

$$\text{calculated length } a_n = 0.99 \times (\text{true length } a_n), \tag{7}$$

where the subscript o indicates the first determination, before subsidence, and n indicates a later determination, after some subsidence has occurred.

The displacement of M in the direction B-M is the change in length of *a*, determined by subtracting eq 6 from eq 7:

$$(\text{calculated length } a_n) - (\text{calculated length } a_o) = 0.99\,[(\text{true length } a_n) - (\text{true length } a_o)]. \tag{8}$$

Therefore, only a 1 pct error in "measured" displacement will be caused by an error of 5 ft in the assumed length of a base line that is about 500 ft long.

The foregoing is an illustration of a very useful principle that often can be applied to advantage in devising a measurement scheme for a particular subsidence study. Namely, there are frequent situations in which significant savings can be achieved in man-hours, equipment, or the permanent field installation by deliberate choice of a procedure or arrangement that contains a constant error (bias) or a small percentage error, because of the fact that the significant information developed by subsidence measurements is the amount of *change* that occurs at a point or between a pair of points, rather than the precise geodetic *locations* of those points. That is, high-precision subsidence measurements can be obtained without necessarily making highly precise determinations of the positions of points on the earth's surface. This principle does not in any way lessen the need for very careful work on the part of the surveyor, without which the measurement data will contain errors that cannot be removed.

The intersection method can also be applied to determine the position of a subsidence monument by use of an electronic distance-measuring instrument. Referring again to Figure 4, the distances *a* and *b* must be measured from each end of the base line. Then, the angle B can be determined by the law of cosines:

$$\cos B = (a^2 - b^2 + c^2)/2ac. \tag{9}$$

The azimuth or bearing of the monument from point B is obtained from the bearing of the base line and the calculated angle B. The coordinates of M are calculated from those of B, using the length and bearing of *a*.

Determination of horizontal offset.

A modification of the intersection method consists of determining the "offset" of a subsidence monument, that is, the component of its displacement at right angles to a specified horizontal reference line (or vertical reference plane). An observation point is placed at one end of the reference line, Figure 5, and the subsidence monuments are placed on or very near to the reference line.

The so-called alignment method, used in Europe for studies of dam displacement, consists of observing through a special "alignment telescope" from the observation point to a second fixed point, for example A in Figure 5, which is placed at the opposite end of the reference line, thus establishing the reference line through the two fixed points. A special target is placed on the subsidence monument that is to be observed. The position of this target is adjusted along a graduated scale, perpendicular to the reference line, until it coincides with the reference line of sight, and then the scale reading is recorded. One man is needed for observing and one to adjust the target. This operation is

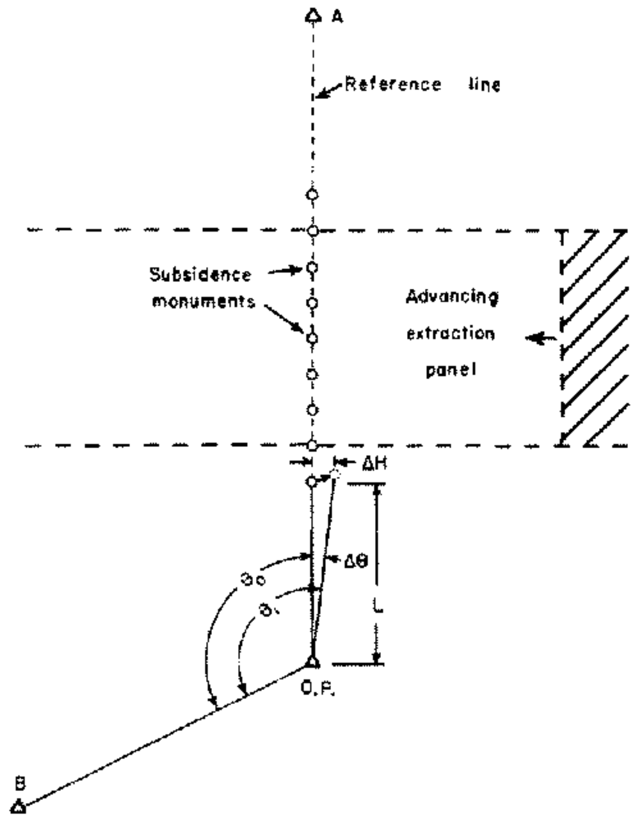

Figure 5. Measurement of displacement ΔH perpendicular to a reference line, using an observation point (O.P.) and a reference point (A or B).

repeated at intervals. The offset or displacement of the subsidence monument is equal to the change in scale reading, ΔH, of the successive target positions.

The offsets of the subsidence monuments can instead be obtained by observing through a theodolite from the observation point. A non-adjustable target is placed on each subsidence monument. A fixed reference point is required, but it need not be on the reference line through the subsidence monuments; it can be placed at any convenient location, for example B, Figure 5. Before any displacement occurs, the initial horizontal angle is measured from the reference point to each subsidence monument. Subsequently, at intervals, the angle θ from the reference point to each subsidence monument is again measured, and the change of angle $\Delta\theta$ is calculated. The component of displacement ΔH at right angles to the reference line for any subsidence monument may be calculated from

$$\Delta H = L \cdot \tan \Delta\theta, \quad (9)$$

where L is the horizontal distance from the theodolite to the subsidence monument (L need not be determined with high precision).

Determination of offset by measuring angular displacement in this way has an advantage in that a special alignment telescope is not needed; a special adjustable target is not needed; personnel need not go into the subsidence monument area; and the fixed point need not be on the reference line but can be at any location that is convenient, considering the surface topography and the probable area to be disturbed by subsidence.

SURFACE MOTION IN A VERTICAL PLANE

In a vertical plane, motions that are of interest are the vertical displacement, the angle of inclination (tilt), and the curvature. Although vertical displacement is the most striking single characteristic of subsidence it is not the major cause of structural damage; nevertheless, it is a convenient indicator of the stage of subsidence activity. Other reasons for determining vertical displacement are the relative ease of measuring it with good precision and the fact that tilt or inclination can be derived from the subsidence profile. Tilt at surface points can also be obtained by direct measurement of the angle of inclination; tilt and vertical displacement are usually interconvertible, one to the other. Curvature probably is most conveniently obtained by calculating it as the change of inclinations per unit of distance along the subsidence profile. The discussion that follows is oriented to methods for determining the vertical displacement profile, which contains the essential information for analysis of motion in a vertical plane. The principal methods for determining vertical displacement are by trigonometric leveling, by differential leveling, and by tilt measurement.

Trigonometric leveling.

The procedure consists of making repeated determinations, over a period of time, of the vertical distance to each subsidence monument from a fixed observation point. This is done at the observation point using a theodolite to measure, in a vertical plane, the angle i to the monument from the horizontal plane through the theodolite. The vertical distance from the observation point to the subsidence monument is calculated from

$$\text{Vertical distance} = H \cdot (\tan i), \quad (10)$$

where H is the horizontal distance from the observation point to the subsidence monument. The vertical displacement of any subsidence monument is the change in vertical distance that occurs from one survey to another. For example, the change that occurs from the initial survey to the nth survey is calculated from

$$(\text{Vertical displacement})_{o\text{-}n} = (\text{Vertical distance})_n - (\text{Vertical distance})_o. \tag{11}$$

From eqs 10 and 11 it can be seen that H need not be known with great accuracy. An analysis can be made here, for the baseline in the intersection method, to show that a 1 pct inaccuracy in H creates only 1 pct error in the calculated vertical distance and vertical displacement.

The angle i, however, must be measured to relatively high precision, employing a theodolite that has a vertical circle sensitivity on the order of 1/2 second of arc. Careful work is required on the part of the observer, in order that random errors of observation may be controlled, because an error of 1 second in measuring the angle i will create an error of about 0.005 ft in the calculated vertical distance to a subsidence monument that is 1,000 ft from the observation point. A precision of ±0.01 ft can ordinarily be achieved by this method, for monuments 800 to 2,000 ft from the observation points.

For each survey, beginning with the second, the subsidence profile(s) along the desired line(s) is constructed by drawing a smooth curve through a plot of the vertical displacements calculated from eq 11.

The tilt at any surface point is the slope or angle of inclination of the tangent to the subsidence profile at that point. Values of tilt may be determined from the curve by various graphical or numerical procedures.

The average curvature between two points on the subsidence profile is the change in angle of inclination per unit of distance between them. The average curvature from one subsidence monument to another may be calculated from

$$(\text{Curvature, Monument 1 to Monument 2}) = \frac{\text{Tilt, Mon. 2}) - (\text{Tilt, Mon. 1})}{\text{Distance, Mon. 1 to Mon. 2}} \tag{12}$$

Differential spirit leveling.

The procedure consists of making repeated measurements, over a period of time, of the vertical distance between each pair of adjacent subsidence monuments along the desired subsidence profile(s). This is ordinarily done by observing with a leveling instrument the horizontal line-of-sight intercept on a vertical graduated rod that is held first on one subsidence monument and then on the other. The vertical distance is calculated from

$$(\text{Vertical distance, Monument 1 to Monument 2}) = (\text{Rod reading, Mon. 1}) - (\text{Rod reading, Mon. 2}). \tag{13}$$

A precise leveling instrument should be used, of the type that utilizes an optical micrometer (direct reading to about 0.005 inch), which displaces the telescope line of sight up or down and thus eliminates the rod-man's operation of adjusting a target on the rod. The rod should be of the type that carries the graduation marks on an invar tape. In use, the vertical position of the rod should be verified by means of a level-bubble attachment. A precision of about ± 0.005 ft can ordinarily be expected by this method.

Assuming that each survey includes measuring in this way, the vertical distance between one of the subsidence monuments and a fixed point not subject to subsidence, then the vertical displacement of each subsidence monument with respect to an undisturbed horizontal reference plane can be calculated as follows, using monument No. 3 of a series as an illustration:

$$(\text{Vertical distance, Mon. 2 to Mon. 3})_n - (\text{Vertical distance, Mon. 2 to Mon. 3})_o = (\text{Change of vertical distance, Mon. 2 to Mon. 3})_{o\text{-}n}) \tag{14}$$

where the subscripts o and n refer to the initial and nth surveys, respectively. Now,

$$(\text{Change of vertical distance, observation point to Mon. 1})_{o\text{-}n} + (\text{Change of vertical distance, Mon. 1 to Mon. 2})_{o\text{-}n} + (\text{Change of vertical distance, Mon. 2 to Mon. 3})_{o\text{-}n} = (\text{Change of vertical distance, observation point to Mon. 3})_{o\text{-}n} = (\text{Vertical displacement of Mon. 3 with respect to an undisturbed horizontal reference plane}). \tag{15}$$

The displacements calculated from eq 15 are plotted to construct the subsidence profile, from which the tilts and curvatures can be derived by calculations, as described for trigonometric leveling.

The vertical displacement of a subsidence monument calculated by cumulation in this way is subject to the cumulation of the errors of measurement of the vertical distances between adjacent monuments. This difficulty is unavoidable with respect to constructing the subsidence profile or in any other situation where the vertical displacement is the quantity needed for an evaluation or a comparison.

If, on the other hand, the comparison can be based on the *change* in vertical distance between adjacent monuments, observed between the initial and the nth surveys, then this change should not be calculated from cumulative displacement values given by expressions such as eq 15, but should instead be calculated directly from expressions such as eq 14.

Tilt measurement.

The procedure consists of making repeated measurements, over a period of time, of the angle of inclination of each subsidence monument. This is done by placing an inclinometer or tilt meter into contact with a set of supporting points (e.g., three stainless steel balls), which are permanently attached to the subsidence monument, and adjusting the inclinometer so as to level a sensitive striding bubble. With the configuration shown in Figure 6, tilt can be measured in three directions 120° apart, so that the direction and magnitude of maximum tilt can be calculated.

The adjustment is commonly provided by a micrometer screw, which raises or lowers one leg of the bubble support by an amount that is determinable to within 0.0001 inch. Denoting by v_o and v_n the micrometer screw settings for the initial and the nth surveys, then the change in the micrometer screw setting at a given subsidence monument is $\Delta v_n = v_n - v_o$.

Denoting by h the "gage length" or distance between the inclinometer support legs, then $\Delta v_n/h$ is the slope of the subsidence profile at the subsidence monument. If $\Delta v_n/h$ is measured at a series of subsidence monuments that are H distance apart, then, from similar triangles,

$$\Delta v_n/h = \Delta V_n/H, \qquad (16)$$

which enables one to calculate ΔV_n, the vertical displacement of a subsidence monument with respect to the adjacent monument, for the nth survey. This subsidence profile for the nth survey can be constructed by cumulating the series of values of ΔV_n, as in eq 15, beginning from an undisturbed point of reference. To construct an accurate curve in this manner, sometimes referred to as the "tangent method," the inclination must be measured at intervals H that are small enough so that the tangent straight-line segments, which are the basis for eq 16, provide a good approximation to the subsidence curve.

Since the subsidence profile can be constructed either from measurements of tilt or of vertical displacement, choice of the appropriate method depends largely on the sensitivity and precision that can be achieved by the two methods. An equivalence between tilt and vertical displacement measurements can be derived from eq 16, let Δv be the change in micrometer screw setting that corresponds to the error of a tilt measurement, and ΔV the precision of determination of vertical distance by trigonometric or differential leveling. When the equality, eq 16, holds true, the inclinometer yields vertical displacements to within the same precision as leveling, considering the distance between subsidence monuments as well as the actual precisions of the measuring devices that are being compared. The precision of leveling, ΔV, can be assumed to be independent of the distance, H, between subsidence monuments, because H will ordinarily be less than 200 ft. Consequently, it follows from eq 16 that if H is halved, the error of tilt measurement can be doubled without changing the relative precisions of tilt and vertical displacement. That is, comparison will tend to favor tilt measurement over leveling as the distance between monuments decreases.

Finally, making use of the fact that $\Delta v/h = 5 \times 10^{-6}$ corresponds approximately to 1 second of arc, the equivalence relation can be expressed in terms of tilt angle as follows:

$$T_e = 200{,}000\, V_e/H, \qquad (17)$$

where

T_e = precision (seconds of arc) of determination of vertical displacement by measuring angle of inclination,

V_e = precision (ft) of determination of vertical displacement by leveling, and

H = horizontal distance (ft) between subsidence monuments.

Eq 17 shows that, with respect to determination of vertical displacements, an inclinometer precision of ± 10 seconds of arc is equivalent to a leveling

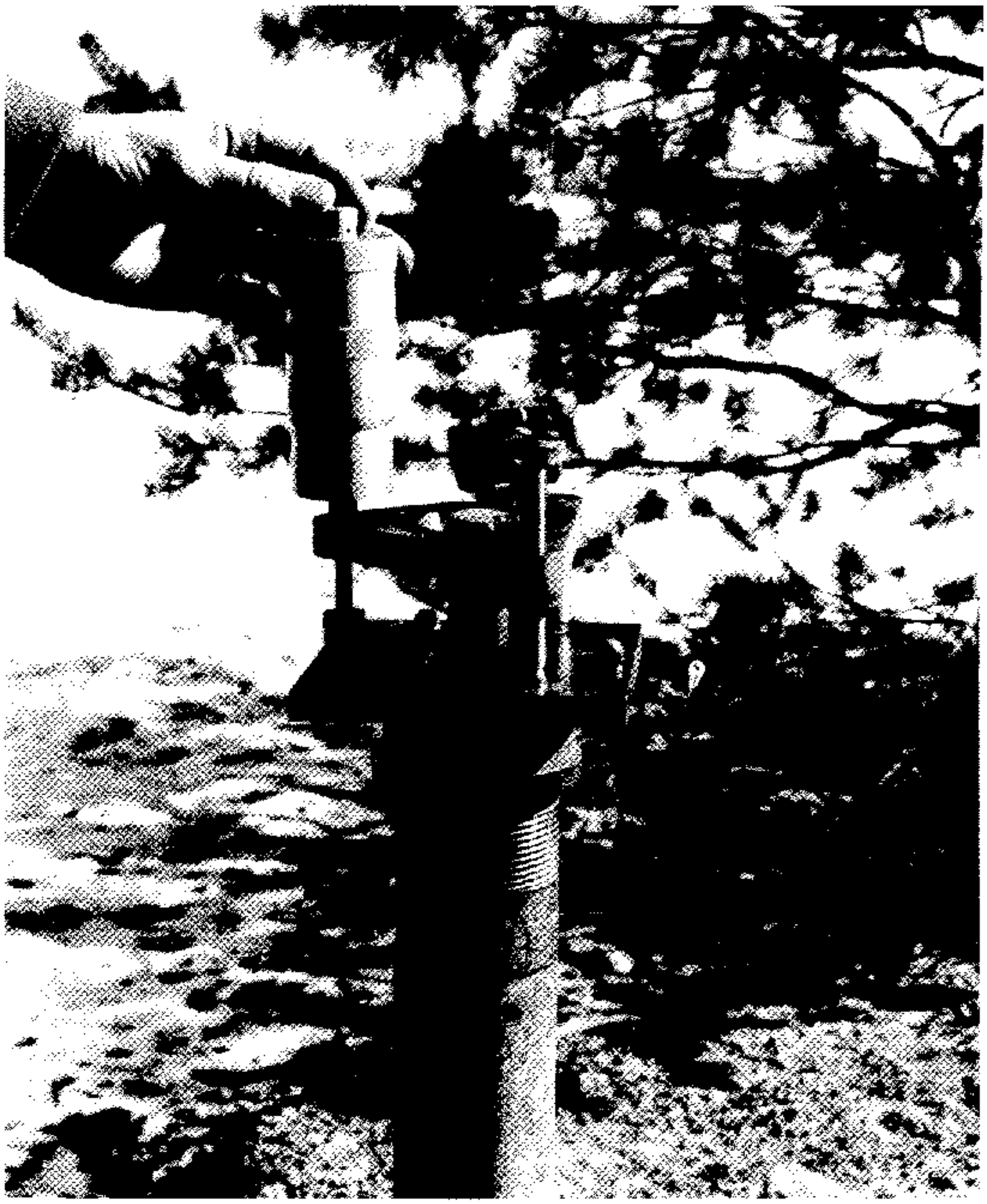

Figure 6. Leveling USBM tilt meter on a subsidence monument. Tilt meter support plate with steel balls is permanently attached to the monument.

precision of ± 0.001 ft, considering determinations that are made for points 20 ft apart.

A tilt meter or inclinometer with a sensitivity on the order of 10 seconds of arc, which ordinarily will be adequate for a subsidence study, is not difficult to construct from commercially available components. A tilt meter of the type shown in Figure 6, for example, can be constructed for about one-half the cost of a precision level. Little skill or training is required to obtain accurate measurements with it.

On the other hand, a tilt measurement system requires that a special set of contact points be permanently attached to every subsidence monument. The contact points and the supporting legs of the tilt meter must be designed so that the elevation of each support point can be reproduced to extreme precision each time the tilt meter is placed on the monument. For example, the height variation at each contact point of a 5-inch-gage-length tilt meter must be less than ± 0.0002 inch in order to limit the angular variation to ± 10 seconds of arc due solely to variability in positioning the tilt meter on the monument in successive surveys.

SUBSURFACE MEASUREMENTS

The objective of a subsurface subsidence investigation, which ordinarily will be coupled with a surface measurement program, is primarily to delineate the structural characteristics and behavior of the strata overlying the seam that is being extracted, in order to develop a structural model for predicting surface subsidence effects.

Structural parameters that are of primary importance are the thicknesses of the rock layers, their strengths, deformation moduli and densities, and the spacing and attitude of rock joints, faults, and fractures. These properties can be determined in one or more drill holes by some combination of the following methods:

1. Examination of drill cuttings to identify rock types and strata thicknesses.
2. Core drilling, to obtain specimens for laboratory testing to determine rock deformation moduli, densities, and strengths.
3. Examination of the drill hole interior by borehole television probe or borehole camera, to identify rock types, strata thicknesses, and the spacing and attitude of rock joints, faults and fractures.
4. Borehole logging by geophysical techniques, to determine strata thicknesses, densities, and deformation moduli.

If the borehole is to remain open, extensometers, strain meters, or joint meters can be installed at selected horizons to measure relative vertical displacements or to detect strata separations. Borehole diameter gages can be installed to detect changes of horizontal rock stresses at selected horizons. Also, reexamination of the drill hole by borehole television or borehole camera is very desirable after subsidence occurs, but is subject to the risk that rock spalls may eventually block the hole.

If the borehole is to be grouted, borehole pressure cells can be installed at selected horizons to detect changes of horizontal rock pressure; an electrical conductor can be installed throughout the length of the drill hole as a "break cable" to indicate the location of strata separations by loss of continuity or by excessive extension or shearing.

Most significant of all, a special casing can be grouted throughout the drill hole to serve as a fixed guide or reference for a special traveling probe that contains an inclinometer. From measurements of the angle of inclination taken at regular intervals along the drill hole, the horizontal displacements of individual points can be calculated, and the profile of the drill hole can be constructed in the manner previously described under "tilt measurement."

The Bureau of Mines has just developed an automatic recording borehole inclinometer probe, which transmits measurement data at regular intervals as it is raised or lowered at uniform speed inside the cased drill hole. The probe provides continuous sensing of the depth, the azimuth, and the inclination in two orthogonal directions, from which one can calculate the displacement, in three dimensions, for any point along the drill hole. Sensitivity of the inclination measurements with present readout instruments is about 24 seconds of arc over the range 0-90 degrees, or about 2.4 seconds of arc over the range 0-10 degrees.

We are planning to modify the automatic recording inclinometer probe for operation inside a horizontal casing, which could be installed in the subsoil by backfilling it in a trench or inserting it in a borehole. As compared with a line of subsidence monuments, such a buried reference base would be much less subject to extraneous disturbances, such as weather, animals, vehicles or spurious tilt, and need not interfere with normal use of the surface, such as for agriculture, transportation or a building foundation. This scheme is capable of yielding all the horizontal and vertical displacements required for completely specifying the surface subsidence behavior. The time required for data acquisition would be reduced to the vanishing point.

CHOICE OF MEASUREMENT SYSTEM

Considering the number of different measuring instruments available and the different methods of determination that can be used, there is a substantial number of combinations that can be employed to carry out a subsidence measurement program, depending on the following factors:

1. Objectives of the study.
2. Size and topography of the surface area to be included in the study.
3. Profiles along which monuments are to be installed.

4. Instruments and methods of determination to be employed.
5. Spacing, number, and type of subsidence monuments, observation points, instrumentation drill holes, etc.
6. Investment required for the instruments and for the field installations.
7. Duration of the study; frequency of surveys.
8. Manpower required to make the measurements and reduce the data.

No single combination of methods will be the optimum with respect to all of the above considerations. Some of the more obvious combinations and their characteristics are as follows, considering surface measurements only.

Survey by theodolite alone.

Horizontal motion by intersection; vertical motion by trigonometric leveling.

The instrument is of moderate cost and can be used also for other surveying work.

Once the monuments are installed, there will be no need for personnel to enter the subsidence area, a notable advantage of this method.

The method lends itself to measurements over a large area.

All measurements can be done by one man.

Surveys by tape and level.

Horizontal motion by taping; vertical motion by differential leveling.

The instrument is of moderate cost and can be used also for other surveying work.

Personnel must do all the measurement work in the subsidence area.

Two-man crew required, at least for leveling.

Reduction of data is simple.

Surveys by electronic distance-measuring instrument and level

Horizontal motion by distance-measuring instrument; vertical motion by differential leveling.

Two instruments are required, one of moderate cost and one quite expensive (distance-measuring instrument) although rental may be feasible.

Personnel must enter subsidence area for all measurement work.

Two-man crew required.

Surveys by tape and tilt meter.

Horizontal motion by taping; vertical motion by tilt meter.

The instrument is relatively inexpensive.

A large number of monuments may be required if a large area must be covered.

The method lends itself to measurements in a small area.

Personnel must do all measurement work in the subsidence area.

One man can make all measurements if monuments and tape are appropriately constructed.

Examples.

Figures 7 and 8 are examples of two schemes employed by the Bureau of Mines for recent subsidence studies. Figure 7 involves subsidence over an iron-ore mine, where surface caving was expected. The objectives were to detect the limits of surface subsidence, to determine its rate of progress, to determine if it is possible to give advance warning of the location of an impending breakthrough to surface, and to document the characteristics of the developing subsidence basin. Surveying by theodolite achieved a precision of about ±0.01 ft for both horizontal and vertical displacements of the subsidence monuments (Fig. 3 shows an observation point). Surveys were performed one to three times each year for about 6 years. Each survey extended over a period of 1 to 2 weeks, depending on the weather. Distances to the monuments from the observation points ranged from about 800 ft to

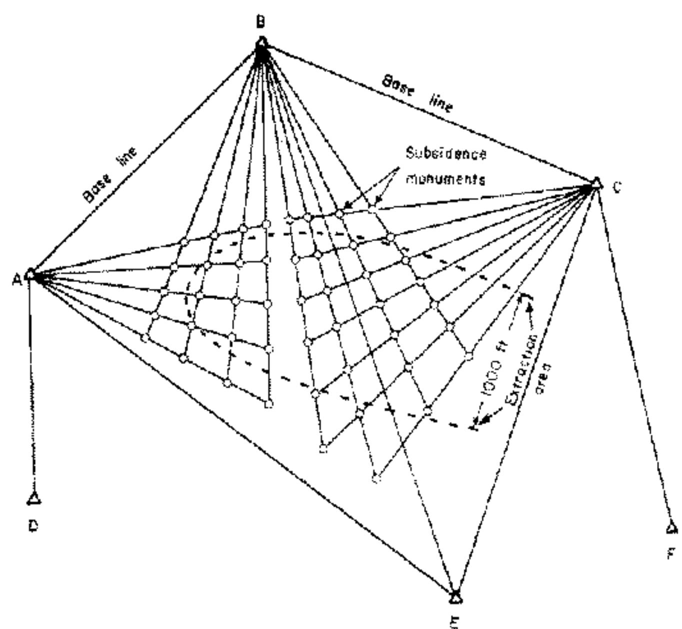

Figure 7. Example of surface subsidence measurement: Intersection method. Theodolite observation points A, B, C; reference points D, E, F.

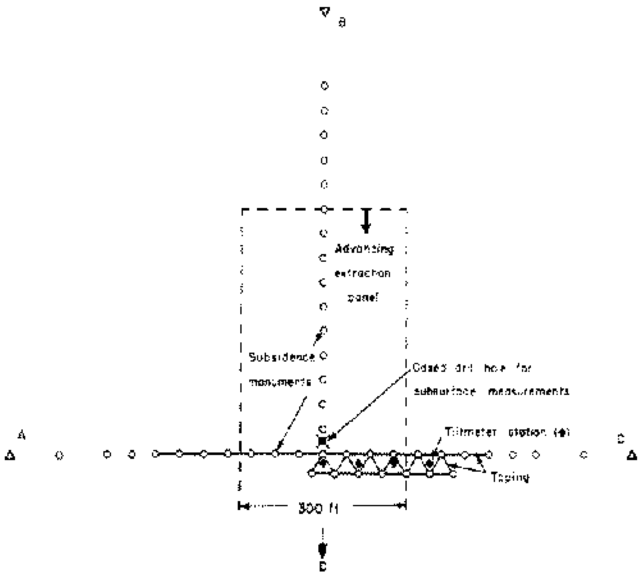

Figure 8. Example of surface subsidence measurement. Observation points A, B; reference points C, D. Leveling on all monuments.

about 2000 ft. As many as 85 subsidence monuments were observed during any one survey. In addition to observing subsidence monuments and the observation point at the opposite end of the base line, two reference points were observed from each observation point as a check on its stability.

Figure 8 involves subsidence over one extraction panel of a coal mine. The objectives were to determine the maximum subsidence, the maximum tilt, the maximum horizontal strain, and the subsidence profile, and to relate these quantities to the behavior of the overburden as calculated from a theoretical structural model. Tilts, measured with a tilt meter, and horizontal strains, measured with a tape, were determined as the panel approached and passed the chain of subsidence monuments across the panel (rosette patterns, to determine direction and magnitude of maximum tilt and maximum strain), thus providing measurements at different points along the subsidence profile by use of the same set of monuments at different stages of development of the subsidence curve. One subsidence curve was obtained from the tilt measurements; another was obtained by differential leveling on the monuments that were located along the axis of the panel. Horizontal north-south displacements of the subsidence monuments located along reference line A-C were measured by the offset method, observing from A with a theodolite. Horizontal east-west displacements of the chain of monuments were measured by the offset method with respect to reference line B-D.

Throughout the drill hole, which extended down almost to the coal bed, were grouted a coaxial "break cable" and an inclinometer casing; outside the casing, a borehole pressure cell was grouted every 100 ft. During drilling of the hole, cuttings were collected for petrographic identification. Upon completion of drilling, the hole was logged by geophysical methods to determine deformation moduli, densities, and thicknesses of the strata.

Neither of these two examples was a comprehensive subsidence study. Each was designed to provide specific subsidence information as well as to determine the capabilities of promising measurement techniques. Continuing development of new techniques will reduce the cost of subsidence studies and thus promote their increasing application.

SUMMARY

Sufficient theory and general principles are available to adequately correlate and interpret subsidence observations and measurements. From the assortment of measuring instruments that is available, a number of combinations can be formed to obtain the measurements that are needed to adequately specify the subsidence behavior. Reliable procedures are given here; more sophisticated techniques are being developed.

For prediction of subsidence disturbances, some progress has been made in analytical studies of the behavior of an undermined rock mass, especially by the finite element method of structural analysis, which relies heavily on the use of modern computers. This approach is handicapped by the cost and physical difficulties entailed in establishing the values of the significant structural parameters, which are the thicknesses, strengths, densities, deformation moduli and jointing patterns of the rock strata that comprise the overburden.

Systematic progress, however, can be achieved by initiating a program of field measurement of the displacements, strains, and tilts, which accompany the progress of extraction. More subsidence data are needed in order to construct and verify theoretical structural models which can be used to predict subsidence components for geological conditions that are typical of those where extraction is being done. Data developed at any given extraction operation will not suffice to predict subsidence parameters a few miles away, without a knowledge of how to take account of changes in the structural characteristics of the overlying rocks, which is one purpose of the structural model. In this approach, measurements taken at several different extraction operations can be combined to provide a predictive capability much beyond what a single company can achieve.

Experience shows that any company engaged in extracting minerals from the earth should conduct at least a token program of subsidence measurements, in order to protect against unexpected occurrences caused by ground movement. Interpretation of a significant ground disturbance and evaluation of future stability depends in large part on the availability of past trends, which can provide a basis for judgment.

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