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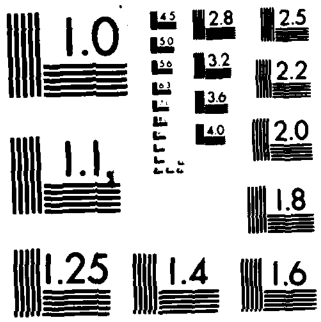

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An instrument to monitor the tilt of large structures

Kenneth Robertson

April 1983

U.S. ARMY CORPS OF ENGINEERS
ENGINEER TOPOGRAPHIC LABORATORIES
FORT BELVOIR, VIRGINIA 22060

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The long-term or short-term tilt of structures such as locks or dams may be measured with an automatic level that has been temporarily modified for the purpose. The modifications consist of the addition of an autocollimating eyepiece and an optical vernier. A calibration mirror is also required for the measurement of long-term tilt. Accuracies of 1 to 5 seconds of tilt may be obtained.

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CONCLUSIONS

A simple and inexpensive instrument has been devised for measuring tilt in large structures. The instrument uses a Zeiss Ni 2 level equipped with an autocollimating eyepiece and an optical vernier to measure the tilt of mirrors that are rigidly and permanently mounted to the structure. A special two-sided mirror is used for calibration so that all measurements are referred to the local vertical or direction of gravity. Laboratory tests have shown the instrument to have an accuracy and repeatability of about one second of arc. Field tests of the instrument have shown that after mirrors mounted in a dam have been stabilized, measurements of tilt can be made with an accuracy of about 2 to 3 seconds of arc. The instrument also gives equal or better results in measuring tilt of lock walls during the fill-empty cycle.

It is believed that the program has met its objective of producing a simple technique for measuring tilt that may be used as a supplement or replacement for the plumb bob used in many concrete dams. The instrument produced during the program is suitable in its present version for use by the Districts. The mirror mounts took an unexpectedly long time to stablize, but finally yielded acceptable results.

PREFACE

The effort covered by this report was conducted under the Civil Works Surveying and Mapping R&D Program, Work Unit 361-31749, "Monitoring Devices for Large Structures."

This work was done under the supervision of Mr. Frederick M. Gloeckler, Jr., Chief, Precise Survey Branch, Mr. John G. Armistead, Chief, Surveying and Navigation Division, and Mr. Eugene P. Griffin, Director, Topographic Developments Laboratory.

COL Edward K. Wintz, CE, was Commander and Director, and Mr. Robert P. Macchia was Technical Director of the Engineer Topographic Laboratories during the study and report preparation.

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INTRODUCTION

Large structures such as locks and dams need to be continuously evaluated to insure their structural safety and stability. Such evaluations should be supported by programs of instrumentation that will provide a means of detecting structural distress or abnormal operating conditions. One vital piece of information is the degree to which a structure tilts or bends under load.

Engineer Manual EM 1110-2-4300, Instrumentation for Concrete Structures, remarks that instruments of this type should be "...designed to accurately measure bending, tilting, or deflection of concrete structures resulting from external loading to the structure, temperature changes within the structure, or deformation of the foundation. Through the measurement of structural deformations they will furnish information in regard to the general elastic behavior of the entire structure and foundation, provide a means for determining the elastic shape of the deflected structure which will permit separation of load deflection and the thermal deflection components, and, with precise alignment data, provide for estimating the amount of translation or sliding."[1]

Normally these measurements are made through the installation of a plumbline, an inverted plumbline, or an optical plummet. Tilt is inferred from the displacement of the plumb bob and the length of the line. Measurements of displacement at intermediate points along the plumbline give information regarding bending of the structure in the vertical direction. Plumb bobs, however, suffer from some serious drawbacks. They are expensive. The installation of a plumbline in a single monolith may cost as much as $50,000, and it must be installed during the construction of the dam. Because of this, usually only one or two monoliths in a dam are equipped with a plumbline. In addition, plumblines lack sensitivity near their points of suspension, necessitating the use of an inverted plumbline. To monitor bending in a monolith both types may be required. Finally, plumblines lack sensitivity on shorter structures. A deflection of 10 seconds in a structure 20 meters high gives a deflection to a plumbline of only 0.1 millimeter.

Because of these drawbacks, it is believed desirable to have an alternative or a supplement to the plumbline. The object of this work has been to develop an instrument and techniques that will permit the direct

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[1] U.S. Army Corps of Engineers, Instrumentation for Concrete Structures, Engineer Manual 1110-2-4300, 15 Sep 80.

measurement of tilt at any point within a dam or other structure where a gallery or room enables observations to be made.

As originally conceived, this device would require three elements:

1. A component, permanently installed within a gallery of the dam, that will undergo the same angular changes as the structure.

2. An instrument that can measure small changes in the angular orientation of this component.

3. An absolute reference, against which the angular changes of the structure can be compared.

In addition to the above, the device should meet the following criteria:

1. It should measure tilt with an accuracy of approximately 2 seconds of arc and have a range of at least 10 minutes of arc.

2. It should be portable.

3. It should be easy to use and should require less than 10 minutes per measurement.

4. It should be inexpensive.

5. It should be able to measure long-term as well as short-term tilt, so that data can be compared over a period of years. (A means of correcting for drift must be incorporated into the system.)

There are several ways of measuring small changes in angular orientation, but two in particular are worthy of special note. The first is the sensitive bubble level. These levels have been in use for many years as a means of leveling instruments, and a commercial model of a tilt-monitoring device called an "Electrolevel" uses a spirit level vial filled with an electrically conducting liquid and a set of three electrodes to monitor the position of a bubble. The instrument may be read remotely by means of a bridge circuit and a meter. The level vial head must be left at the site; consequently, if it is desirable to monitor more than one point, a separate head must be purchased for each point. The cost per head is in excess of $3,000.

The second method of measuring small changes in angular orientation is by using an autocollimator. The autocollimator is an optical device that projects a collimated beam of light against a mirror. The reflected light reenters the autocollimator, and the difference in angle between the projected light and the reflected light may be measured with a high degree of accuracy. Devices of this nature have been in use in the laboratory and in the optical tooling industry for many years, and are sold commercially. Several reference books are available that detail the operating principles and uses of autocollimators.[2]

Because of its sensitivity, long-term stability, accuracy, and range, the autocollimator was chosen to be the element for measuring small changes in angular orientation for this work unit.

Because an autocollimator is designed to measure changes in angle of a mirror, a mirror becomes the element that, when affixed to the structure being monitored, will undergo the same angular change as the structure.

The third element required is an absolute reference against which the angular changes are measured. (If the mirror and autocollimator were permanently mounted in a gallery of a dam, both would tilt together as the dam tilts and no angular displacement of the mirror would be detected relative to the autocollimator.) The simplest reference is the gravity vector. If the autocollimator's optical axis could be made perpendicular to the direction of gravity, a measurement could be made of the mirror's change in angular orientation with respect to the vertical, and tilt of the structure could be detected.

APPROACH

It appeared at the beginning of the work unit that the most difficult task, if the three elements listed above were involved, would be to find a method to make the autocollimator axis exactly horizontal.

Two approaches were attempted. The first involved the use of a pendulum mirror. This device consists of a pendulum suspended from a pair of knife edges in a damping medium. Above the knife edges, a two-sided mirror is mounted, and the pendulum may be adjusted to make the mirror vertical. The mounting of the mirror is arranged so that it can be viewed from either side. Further, the two faces of the mirror are ground to make them parallel to a high degree of precision.

To use the pendulum mirror, the autocollimator is alined as nearly as possible to be horizontal and pointed at one face of the mirror. A reading is taken of the mirror with the autocollimator. The mirror with its suspension system is then carefully rotated through 180 degrees so that the other mirror face can be seen by the autocollimator, which has

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[2] K. J. Hume, Metrology with Autocollimators (London: Hilger & Watts Ltd., 1965)

remained fixed in place. Next, the second face is read. During the rotation, the pendulum will hold the mirror faces at the same angle with respect to the vertical. If the mirror had been exactly vertical, both faces would give the same reading. The usual case, however, is for the mirror to be slightly tilted. When this tilt occurs, the reflection from the first face will be projected slightly above or below the horizontal. When the second face is read, it will give a reading equal in value but opposite in direction to the first face. If the mean of the autocollimator readings of the two faces is taken, it will be the value that would be seen if the mirror were exactly vertical. The mirror can then be adjusted to this value and the autocollimator used to check the results. The adjusted pendulum mirror is then a reference for making the autocollimator horizontal. The horizontal axis of the autocollimator having been established, the pendulum mirror is moved out of the way and the autocollimator is used to make a reading of the sample mirror representing the tilt of the structure under examination.

Obviously, the autocollimator must not be moved after it has been adjusted to the horizontal. This means that the pendulum mirror must be used to adjust the autocollimator before the reading of each mirror within the structure, because a movement to a new location would disturb the horizontal axis of the instrument. The cost of the pendulum mirror is presently about $2,500, and the weight is about 15 pounds.

A pendulum mirror obtained from the Brunson Instrument Co. was used with a Hilger and Watts Microptic Autocollimator in a number of tests to determine its suitability. A stationary mirror was measured repeatedly with the pendulum mirror-autocollimator combination. The repeatability of the combination appeared to be about 2 seconds of arc. The test consisted of setting the autocollimator to obtain a return from the test mirror. The pendulum mirror was then placed in the line of sight and the first face of the mirror was read. The pendulum assembly was then rotated 180 degrees and the second face of the mirror was read. The mean of the two readings was then taken and the pendulum mirror was adjusted for verticality. Both faces of the pendulum mirror were again read as a check, and the device was then removed from the sight path. Finally, the test mirror was read and the departure from the vertical was calculated. The positions of the pendulum mirror and the autocollimator were then altered so as to destroy the calibration of the combination. The entire series of measurements were then repeated. Because the test mirror had not been disturbed, the ability to determine its tilt was taken as a measure of the accuracy of the system. This was determined to be about 2 seconds of arc for a single measurement.

The second approach to finding a way to make the autocollimator exactly horizontal was to use a mercury pool as a reference. If mercury is poured into a shallow dish of sufficient diameter to avoid a meniscus effect at the center of the dish, the surface of the mercury becomes a mirror that may be considered to lie in a horizontal plane. If a pentaprism is positioned with one face directly above the mercury pool and the autocollimator is placed approximately horizontal and viewing the other face, the mirror surface of the pool can be seen. The pentaprism rotates the angle of view through exactly 90 degrees and the autocollimator views the mercury pool as if it were vertical. In this way, the mercury becomes a vertical reference for the autocollimator. In use, a reading is first made of the mercury pool, then the pentaprism is moved out of the line of sight, and the test mirror is read. The difference between the reference mercury pool and the test mirror is the angle of tilt.

One problem with the mercury reference is the appearance of small waves on the surface of the mercury. These cause a distortion of the optical pattern seen in the eyepiece of the autocollilmator and decrease the accuracy of the measurements. A way of reducing the amplitude of the waves is to cover the surface of the mercury with a clear damping fluid such as mineral oil. A number of viscosities of damping oil were obtained and used, but none seemed to damp the wave motion adequately. A dampened suspension system was also tried with similar results and because of this effect, which would be magnified in the gallery of a dam by vibrations from the operation of turbines or the action of water falling over the spillway, the use of a mercury pool was finally abandoned.

These two approaches were based on the thinking at the time the work unit was originiated. Of the two, the one using the autocollimator and the pendulum mirror was shown to be workable, but cumbersome in view of the weight of the components involved and the fact that the autocollimator needed to be leveled with the mirror before each measurement.

The investigations were next turned towards the use of an autocollimating eyepiece with the Zeiss Ni 2 automatic level. The automatic level is a common piece of surveying equipment and is light, rugged, and simple to use. It is designed to be mounted on the top of surveyor's tripod and may be set up in a few minutes. The autocollimating eyepiece can be attached and taken off easily and the level returned to its usual function.

An automatic level such as the Zeiss Ni 2 is one that must be leveled only to within a few minutes of arc, at which point a pendulum compensator within the instrument performs the final leveling to the horizontal. Although this final, automatic setting is very reproducible over a period of a day or more, it produces a line of sight that may not be absolutely horizontal. Departure from the horizontal may be as large as 5 seconds of arc. When the instrument is being used as surveyor's level, this is not a serious defect as long as the foresights and the backsights are kept approximately equal. When both sights are in error by the same amount, the difference between the two is the true difference in elevation. This is true as long as the instrument gives a reproducible error in the line of sight. In the case of the Zeiss Ni 2 the line of sight is reproducible to better than 0.5 arc second.

Unfortunately, the level of the instrument eventually does change or may be disturbed by rough handling, and if long term tilt is to be measured, some sort of calibration of the level is required. In addition, the placement of the autocollimating eyepiece would give slightly different results each time it was attached to the instrument, because the reticle of the autocollimating eyepiece would be replaced in a slightly different positon. A different problem arises from the reticle of the autocollimating eyepiece being graduated at 10-second intervals, with estimation of finer readings being dependent on the skill of the operator.

Despite these two drawbacks, the instrument is so convenient to use and so readily available to surveyors that it was decided to try to find a means of overcoming these seeming limitations. The first problem could be solved by the use of the pendulum mirror. The level could be used to autocollimate on each side of the mirror in turn. The mean of the two readings would be the calibration constant for the level and the autocollimating eyepiece. In addition, because the constant of the level would not change over a period of less than a day, several readings of sample mirrors could be made without recalibration, although a recalibration should be performed at the end of the run to see if the level and the autocollimating eyepiece showed any drift.

The second problem could be solved by incorporating an optical vernier into the system so that interpolation could be made between the 10-second intervals of the autocollimator eyepiece reticle. The optical vernier consists of a thin wedge of glass that deviates the line of sight in the direction opposite the point of the wedge. If the wedge is rotated, the line of sight can be deviated up, down, right, or left. In the present case, only deviations in the up or down directions are used. The wedge can be rotated until the line of sight has been deviated sufficiently to match one of the 10-second lines in the reticle. The amount of rotation necessary to bring the lines into coincidence is a measure of how many seconds the line was displaced from the 10-second mark. If the angle in the wedge is large enough, the rotation can be continued until the lines coincide at the next mark. By this technique, the mean of several values can be used as the final result.

Experimenting with the system for a period of time showed that the pendulum mirror could be replaced by substituting a two-sided mirror where the two sides of the mirror were parallel but not hanging from a pendulum. The important property of the automatic level is that, at least over the period of a working day, it produces a reproducible line of sight. Even though this line of sight may not be perfectly horizontal, it will be the same when first one side of the mirror is read and then the other. If the mirror were perfectly vertical, the same reading would be obtained from either side, as the level was moved from one side to the other. If the mirror were not perfectly vertical, the line of sight would be deflected upwards by one side of the mirror and downwards an equal amount by the other side of the mirror. The mean of the two values would be the value obtained had the mirror been vertical. Thus, all that is needed to reference the level-autocollimating eyepiece combination is a two-sided mirror that has two parallel faces. This decreases the weight, cost, and complexity of the system considerably and is the reference element used in the final configuration of the instrument.

In its final form, then, the instrument consists of three components plus a calibration mirror. First is the Zeiss Ni 2 automatic level. There are several other competing levels with comparative qualities, particularly the Wild version. However, the Zeiss is the only one that can be fitted with a standard autocollimating eyepiece that has a reticle graduated over a range of several minutes of arc. The Wild version has an autocollimating eyepiece, but the reticle contains only a crosshair. Because of this, the Zeiss is the only automatic level at present that is known to be suitable, although at some future time it might be possible to retrofit the Wild autocollimating eyepiece with a different reticle.

The second component, of course, is the autocollimating eyepiece. This is graduated at 10-second intervals over a range of plus or minus 7 $^1/_2$ minutes of arc. Conversations with several Engineer Districts have indicated that this is a more than ample range, with most expected movements being less than 2 minutes. The eyepiece can be purchased with its own carrying case and a 110-volt to 6-volt transformer. A 6-volt lantern battery serves as a portable power supply where a.c. power is not available. The eyepiece can be attached to the level and adjusted in about 3 minutes. No modification of the level is necessary and the level may be used to perform its normal surveys when not being used to monitor tilt.

The third component is the optical vernier. This component is not available as a stock item, but must be purchased as several parts and then assembled and calibrated. A description of this process appears later in this report. A small amount of machine work is also required to provide a mounting bracket for the optical vernier. The vernier must be placed in front of the telescope of the level.

Finally, the calibration mirror must also be purchased as several parts and assembled. No calibration of this part is required, although the parallelism of the two faces of the mirror must be assured.

In addition to the instrument, a stable element is required that represents the structure. A stable element moves only as the structure moves, and its tilt can be measured. This is the mirror that is rigidly and permanently mounted against the wall of a gallery inside a dam or on a tripod erected firmly above the lock wall under study.

The stable element must meet several criteria. First, it must be flat; one-quarter of a wavelength of light or better is recommended. It should be aluminized on the front surface and have a protective coating, such as silicon monoxide. The mirror should be approximately 2 inches in diameter and at least one-half inch thick to help prevent distortion of the mirror from strains incidental to mounting. It might be desirable to mount the mirror directly to the concrete wall of the gallery, but this would prove difficult. The instrument used to read the mirror has a range of only plus or minus 7 1/2 minutes of arc, and only by chance would a gallery wall prove to be vertical to that degree of accuracy. Thus, it is necessary to attach the mirror to an adjustable mount, which in turn can be fixed to the wall. This mount should also be designed to minimize strain to the mirror.

Each of these components will now be dealt with in greater detail.

THE AUTOMATIC LEVEL

As the names implies, the automatic level provides the final adjustment of the line of sight automatically. All that is required after setting up the instrument is to center a circular bubble of low sensitivity. At this point a pendulum compensator within the instrument produces a final leveling. Essentially, the compensator consists of three prisms, one of which is suspended by four wires. This prism is free to swing within a predetermined range to compensate for small errors in leveling. According to the manufacturer, the compensator is precise to ± 0.25 second of arc. In this case, precision means that repeated setups of the level will produce the same line of sight if the instrument is not physically abused. The line of sight of the level, including the center of the crosshair, may not be perfectly horizontal, however, and may change over an extended period of time. It is for this reason that a calibration is required to determine the departure of the line of sight from the horizontal when comparative measurements of tilt are to be made over periods that might be as long as several years. For short term measurements, the compensator may be relied on to provide reproducible results without calibration. An example of this second case is where tilt of a lock wall during the fill-empty cycle might be desired. Measurements of this type normally do not exceed 12 hours duration.

In the case of ordinary leveling it is not necessary for the line of sight to be perfectly horizontal if the foresights and backsights are balanced.

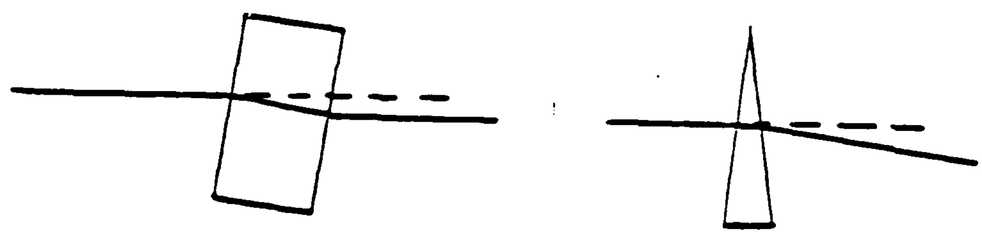
THE AUTOCOLLIMATING EYEPIECE

The autocollimating eyepiece consists of a small lamp, a half-silvered diagonal mirror, a recticle for reading angles, and an additional eyepiece for viewing the reading reticle. When the lamp is turned on, it illuminates the crosshair of the level. The focus of the level is set for infinity, and the objective lens of the level projects an image of the crosshair along a collimated beam against a plane mirror, the tilt of which is to be measured. The mirror, which is usually placed from within a few inches to a few feet from the instrument, reflects the crosshair image back into the level, where it comes to a focus in the plane of the original crosshair. An observer looking into the eyepiece will see both the crosshair and its image, with the displacement between the two being proportional to the degree of tilt of the mirror. The observer will also see the measuring reticle graduated in increments of 10 arc seconds. By the use of this reticle and the displacement between the crosshair and its image, a quantitative measurement may be made of the tilt of the mirror with respect to the optical axis of the level.

In use, the autocollimating eyepiece is attached to the level, and the pair are mounted together with the optical vernier to a baseplate. The calibration mirror is then measured to determine the departure from the horizontal, if any, of the system's line of sight. The departure is used as a correction to the mirrors being read to determine the tilt of the structure.

THE OPTICAL VERNIER

The reading reticle provided in the autocollimating eyepiece is graduated in divisions of 10 arc seconds. A trained observer might be able to interpolate the position of the crosshair to the nearest one or two seconds between divisions, but a better way is to use an optical vernier. This is simply a prism or wedge of glass placed in front of the objective lens of the level that can be used to deviate the line of sight by a known amount. This should not be confused with the parallel plate attachment for the level, which is used as a vernier when a normal leveling course is being run. The parallel plate attachment, as the name implies, uses a thick plate of glass with parallel sides and displaces the line of sight while keeping it parallel with the original line. Figure 1 shows the difference.



PARALLEL PLATE ATTACHMENT   OPTICAL WEDGE

Figure 1. Parallel Plate Attachment Versus Optical Vernier.

If a ray of light passes through a prism, it will be bent in such a manner that its angle of deviation, D, equals (n-1)A, where n is the index of refraction of the prism glass and A is the angle of the prism wedge. A deviation of about 30 seconds appears to be a good compromise between ease of reading and sufficient range of deviation so that different portions of the reading reticle may be sampled. If glass of a refractive index of 1.5 were selected for the prism, the wedge angle should be 1 minute to provide a plus or minus deviation of 30 seconds for the line of sight.

When the wedge is placed in front of the objective lens of the level with its vertex up, the line of sight will be deflected downward through a small angle. If the wedge is rotated about the optical axis of the level, the line of sight will describe a small circle. For this application, only the upward-downward deviations are of interest and the right-left components of the motion may be disregarded. By rotation of the wedge, any deviation of the line of sight can be obtained within the limits set by the wedge angle.

Because it is difficult to grind and polish a prism to the exact angle required, an initial calibration is necessary. The prism should be mounted in the center of a rotary stage that has degree markings around the circumference of the rotating part, with a stationary part that can serve to index the stage. In order to calibrate the prism mounted in the rotary stage, set up a precision autocollimator such as Hilger and Watts

Micrometer Angle Dekkor so that it views a good first-surface mirror placed a suitable distance away. Adjust the autocollimator reticle to read tilt of the mirror about a horizontal axis (seen in the autocollimator as a vertical displacement of the reflected crosshair). This position will represent no deviation of the line of sight. Next, insert the optical wedge between the autocollimator and the mirror. A deviation of the line of sight, due to the insertion of the prism, will be noted. Rotate the prism until the crosshair is restored to its original position indicating no deflection up or down of the line of sight (ignore deflections in the right or left direction). In this position the prism has its wedge pointing right or left. Rotate the wedge exactly 90 degrees. In this position the wedge will be pointing either directly up or directly down , and the deflection of the line of sight will be at a maximum. Measure this deflection with the autocollimator and record the value together with the corresponding angles from the rotating stage. As a check,. do the same calibration starting with the rotary stage at 180 degrees from the original reading (if the first set of data was taken starting with the wedge pointing left, now start with the wedge pointing right).

Next, a scale may be drawn that shows seconds of deviation of the crosshair as a function of the rotation of the wedge. The angle of deviation changes as the sine of the angle turned by the rotation of the wedge. If M is the maximum deviation of the wedge, then M sin A is the deviation of the line of sight when the wedge is rotated through an angle A from its initial position of no deflection.

To use the wedge as an optical vernier, place it in front of the objective lens of the level and adjust the level and autocollimating eyepiece to obtain a reflection from a mirror. Usually the reflection of the level crosshair will not coincide with one of the lines on the reading reticle. Rotate the wedge until the crosshair does coincide. The number of seconds of arc required to bring the two into coincidence should then be added to the reticle reading for a complete measurement of angle. Rotating the wedge an additional 10 seconds should bring the crosshair into coincidence with the next reticle division. Several readings may be made in this way to refine the final measurement.

CALIBRATION MIRROR

It is well known that the line of sight through the crosshair of the automatic level is not perfectly horizontal, but that the amount that it deviates from the horizontal is constant over a period of several days. In addition, when the autocollimating eyepiece is placed on the level, the reading reticle may not coincide exactly with the crosshair of the level. Because of this, there will be a small error in the reading of a mirror when compared to the true vertical. In addition, over a long period of time the line of sight of the level may change, and each time the eyepiece is placed on the level it may be mounted in a slightly different position. Because of these shifts, a means must be found to calibrate the instrument before use so that all measurements, even those taken years apart, will be related to a common base; in this case, the direction of the vertical or gravity vector.

If it were possible to make a mirror perfectly vertical, a reading of the mirror by the instrument should show zero tilt. If it does not, it is because of the errors in the compensator and in the positioning of the autocollimator reticle. Because the mirror is vertical, the total error can be read directly from the reticle and optical vernier, and the results applied as a correction to subsequent readings. In practice it would normally be very difficult to make a mirror truly vertical so that it might be used for calibration. However, because of the reproducibility of the automatic level over a short period of time, a special calibration mirror may be used to find the necessary correction.

The calibration mirror has been ground and polished to have faces that are parallel to within 0.5 arc second. The mirror is mounted to a tribrach in an approximately vertical position and reading of tilt is made of one face with the instrument. Without moving the mirror, the instrument is then used to make a reading of the other face. If the mirror were perfectly vertical, both readings would be the same, and each would contain the error of the instrument. If the mirror were not vertical, the two readings would not agree, but the mean of the two would be the error of the instrument. Thus the calibration of the instrument can be performed by measuring the faces of the two-sided mirror and taking the mean of the two readings. This calibration takes less than 20 minutes and should be performed at the beginning and the end of each day's readings to check for drift in the calibration. Typically, the difference will be less than 2 seconds, and the mean of the two sets can be used to correct the intermediate readings of the mirrors monitoring tilt of the structure.

STRUCTURE MIRRORS

An essential part of the tilt-monitoring system is the structure mirror. This must perform several functions. The mirror must be mounted in such a manner that it accurately follows the tilt of the structure; the mount must not distort the mirror so that an unclear image would be seen in the autocollimator; and the mount must provide a means of setting the mirror to an almost-vertical initial position so that the image of the crosshair will be near the center of the range of the instrument.

Providing a mirror mount that will meet these requirements has proved to be the most difficult part of the work, and additional studies should be made to determine the optimum configuration for the mount. Neverthless, a workable mirror mount has been devised and tested in Philpott Dam in southern Virginia. Two versions of the mount were fabricated and tested, with one of the versions providing superior results.

The first type was a one-piece mount. First, two holes were drilled into the wall of the gallery, one above the other. Lead anchors were then inserted into the holes to accept $^1/_4$-inch screws for the initial placement and adjustment of the mirror mount. The mount itself consisted of a $^3/_8$-inch-thick rectangular plate of aluminum. At the top and the bottom of the plate, holes were drilled to accept the screws that would be inserted into the lead anchors to hold the aluminum plate against the gallery wall. On the back of the plate two small screws were placed, one near each edge, so that the screwheads would act as pivots to permit adjustment of the plate to a vertical position for the initial alinement of the mirror. Finally, three screws with washers were used to hold the mirror flat against the front of the plate. To mount the mirror in the gallery, a layer of structural epoxy was coated on the back of the mounting plate. The back of the plate had first been degreased and roughened with emery cloth. Some of the epoxy was also rubbed into the concrete wall of the gallery. The plate was then pressed against the wall and the two screws were screwed into the lead anchors. Next, the mirror was mechanically mounted against the front of the plate by using three screws and washers. The mirror and mount were then ready for an initial adjustment. While the verticality of the mirror was monitored with the tilt instrument, the upper and lower screws were adjusted until the mirror was within about 10 arc seconds of the vertical, and the mount was left to allow the epoxy behind the plate to cure. After two weeks the mirror was removed and a second type of epoxy was used in a thin layer to affix the mirror permanently to the front of the plate. Finally, a protective cover was placed around the mirror mount and the mount was left for final curing of the epoxy for a month before the first set of readings were taken.

The second type of mirror was much easier to put into place. This mount consisted of two plates of aluminum. The first plate was epoxied to the gallery wall and held in place with a single screw and lead anchor until the epoxy cured. The mirror had been affixed to the second plate with another type of epoxy in advance. After the epoxy behind the first plate had cured, the second plate, with the mirror, was attached to the first by means of two adjusting screws, working in compression against springs, and a ball bearing. The two screws could then be adjusted to provide verticality of the mirror. Although this type of mount seemed to be less rigid, it provided much greater ease of application and adjustment.

EPOXY ADHESIVE

Two types of epoxy adhesive were used to affix the mirrors to the gallery wall. The first epoxy was used to attach the mirror to an aluminum plate. Not only was this epoxy required to hold the mirror rigidly, but it was also necessary that it not distort the mirror during the curing process. Too hard an adhesive would tend to distort, while too soft an adhesive would let the mirror creep and eventually produce a false reading of tilt. Three types of adhesive were tested and the one giving the least distortion to a mirror was chosen. Tests for distortion were performed on a Zygo interferometer. Two examples are shown in figure 2, a-d. The straightness of the interferometer fringes is a measure of the flatness of the mirror. The epoxy chosen for least distortion was "Epoxi-Patch Kit 0151 Clear," manufactured by the Hysol Division of the Dexter Corporation.

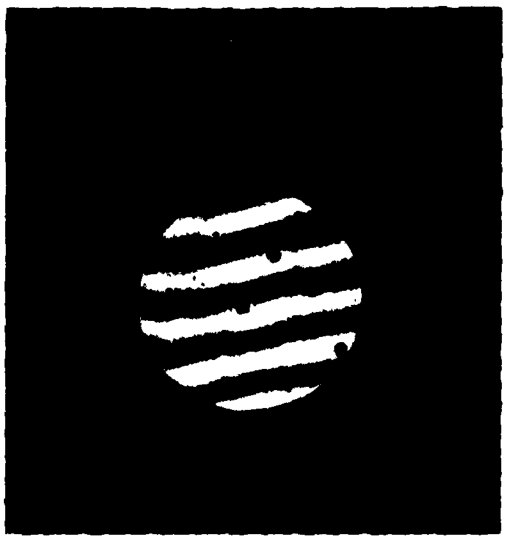
In the case of the one-piece mirror mount it was necessary to affix the aluminum plate to the wall first, using a structural epoxy, and then wait for that epoxy to cure. If this procedure had not been followed, the structural epoxy would have distorted both the aluminum plate and the mirror. This epoxy was allowed to cure for two weeks before the mirror was applied with the Hysol adhesive. With the two-piece mount the mirror could be attached to the adjustable plate in advance.

The second epoxy used was a structural adhesive chosen for its rigidity and strength. It was applied in a thick layer behind the mirror mounts to attach them to the concrete wall of the gallery. The epoxy chosen for this task was "Sikadur 31 Hi-Mod Gel," manufacuted by the Sika Corporation. This material is viscous, supporting a 1/4-inch bead, and has a relatively short pot life of about 30 minutes. It should not be applied to concrete less than six weeks old.

BEFORE
2a

AFTER
2b

HYSOL 0151 EPOXY PATCH KIT
CURED 3 DAYS AT 20° C



BEFORE
2c

AFTER
2d

SUMMER M62 LENS BOND (EDMOND)
CURED 3 DAYS AT 20° C

Figure 2. Effect of Epoxy Adhesive on Mirror Flatness.

LABORATORY TESTS

After the instrument was assembled and the optical vernier had been calibrated, a series of laboratory tests were begun. The first of these tests was for accuracy and linearity. For the test, the instrument was set up facing one side of the double-faced calibration mirror. For the purpose of determining accuracy, a Hilger and Watts Micrometer Angle Dekkor, a precision autocollimator, was used as a standard and was set up facing the reverse side of the calibration mirror. The mirror was then tilted by small amounts throughout the range of the instrument under test, about 15 minutes of arc. Each time the mirror was tilted both instruments were read, and the accuracy of the test instrument was measured by how well it agreed with the Hilger and Watts autocollimator (the degree of tilt would be the same for both instruments, but of opposite sign). Table 1 gives the results of this test. If very high accuracy is required, this test may be used to draw up a correction curve. It may be seen from the table, however, that the errors are quite small, never exceeding one second of arc.

TABLE 1. Accuracy and Linearity

TILT INSTRUMENT (Seconds) (A)	HILGER & WATTS AUTOCOLLIMATOR (Seconds) (B)	DIFFERENCE (Seconds)
-423.2	-423.5	+0.3
-404.3	-405.0	+0.7
-395.4	-395.8	+0.3
-370.2	-370.5	+0.3
-316.4	-316.9	+0.5
-267.2	-267.3	+0.1
-235.0	-235.4	+0.4
-155.0	-155.2	+0.2
-48.9	-48.7	-0.2
-22.1	-23.0	+0.9
*+0.4	*+0.4	0.0
+22.5	+23.2	+0.3
+73.4	+72.8	+0.6
+111.5	+111.9	-0.4
198.0	198.0	0.0
+261.0	+260.3	+0.7
+326.8	+327.1	-0.3
+414.9	+415.2	-0.3

*The Hilger and Watts data were adjusted to agree at a reading of +0.4.
(A) Mean of five readings
(B) Mean of three readings.

The second laboratory test was for stability and reproducibility. For this test a mirror was mounted on an optical pier that was isolated from the surrounding building. The test lasted a week. Each morning the instrument was assembled and readings were taken of the calibration mirror to obtain the departure of the line of sight from the horizontal. During the day several readings were taken of the pier-mounted mirror. At the end of the day final readings were taken of the calibration mirror, and the instrument was disassembled and put away. The mean of the two sets of calibration readings was used to correct the measurements of the sample mirror. Results of the test are shown in table 2.

TABLE 2. Stability

DATE	TIME	UNCORRECTED READING	INSTRUMENT CORRECTION	CORRECTED READING
1/19/81	0950	-74.5	-5.8	-68.7
	1020	-71.5	-5.8	-65.7
	1340	-71.5	-5.8	-65.7
	1420	-71.3	-5.8	-65.5
1/21/81	0800	-70.8	-6.1	-64.7
	1015	-70.4	-6.1	-64.3
	1500	-70.5	-6.1	-64.4
1/22/81	0950	-70.3	-4.6	-65.7
	1000	-70.5	-4.6	-65.9
	1250	-69.8	-4.6	-65.2
	1410	-69.4	-4.6	-64.8
1/23/81	0820	-73.8	-5.9	-67.9
	0840	-72.5	-5.9	-66.6
	0935	-72.3	-5.9	-66.4
	1245	-71.6	-5.9	-65.7
	1425	-72.0	-5.9	-66.1
	1445	-71.5	-5.9	-65.6
1/26/81	0755	-71.3	-7.2	-64.1
	0820	-72.1	-7.2	-64.9
	1335	-72.3	-7.2	-65.1
	1355	-71.1	-7.2	-63.9

The first measurement in the table should probably be disregarded, as the mirror had only been mounted at 0830 that morning and may still have been settling into a final position. The standard deviation of both the corrected and the uncorrected values was about 1.2 arc seconds for the entire set of data. How much of the tilt was due to the instrument and how much was due to minute tilts of the mirror is unknown and would be difficult to determine at such a low level of tilt. The data does show that reproducibility of readings is at the level of about 1.0 arc second.

The final laboratory test involved simulated mounting and reading of a mirror in a dam. A site was prepared in the basement of the Engineer Topographic Laboratories building 2591, a two-story poured-concrete structure. The mirror was of the one-piece type. For the initial installation the mirror had already been attached to an aluminum plate and the assembly was fixed in place with the Sikastix Gel epoxy. As shown in table 3, the curing of the epoxy enabled stable results in only two days. Unfortunately, the curing process had strained the aluminum plate and mirror to the point that the crosshair image seen in the autocollimator was distorted and difficult to read. After three weeks of measurements it was decided to replace the mirror assembly using a technique which would lessen the strain on the mirror. In this case, the aluminum plate was mounted first and the epoxy was allowed to cure for a week. Then the mirror was put in place with the second epoxy. Definition of the crosshair was greatly improved, and this technique was used later in the tests at Philpott Dam. This is also the technique described previously in the section on structure mirrors. Readings were also taken of this mirror and the results are given in table 4. Again, the mirror mount achieved stability within about two days. Movements from that time on are attributable to small tilts of the building wall due to temperature changes.

TABLE 3. First Mirror, Building 2591
Mirror Attached at 1000, 5/5/81

DATE	TIME	READING (Arc Seconds)
5/5/81	1030	13.3
	1100	11.7
	1200	9.3
	1230	9.1
	1300	9.5
	1400	14.6
	1420	16.7
	1500	21.5
5/6/81	0930	65.2
	1430	63.7
5/7/81	0715	60.9
	1430	56.0
5/8/81	0830	57.0
	1430	52.8
5/11/81	0840	54.8
	1430	58.3
5/12/81	1100	59.1
5/13/81	0820	55.9
	1430	54.6
5/29/81	0730	52.5

TABLE 4. Second Mirror, Bldg 2591. Mirror Attached at 1000, 6/2/81

DATE	TIME	READING
6/2/81	1500	7.3
6/3/81	0800	14.6
	1030	17.4
6/4/81	1030	32.6
	1500	32.5
6/8/81	1015	36.2
	1500	37.2
6/9/81	0900	40.0
	1435	39.6
6/11/81	1430	38.0
6/12/81	0950	38.9
	1445	36.7
6/15/81	0830	48.6
	1430	49.4
6/17/81	0800	59.4
	1430	50.3
6/19/81	0930	36.4
	1410	39.2
9/9/81	1020	44.6
	1210	43.0
9/10/81	1030	44.8
	1230	42.9

During the first day, the mirror was adjusted several times. The final adjustment was made immediately prior to the 1500 reading.

FIELD TESTS

Arrangements were made with the U.S. Army Corps of Engineers Wilmington District for tests of the tilt-monitoring system at Philpott Dam in southern Virginia.

Philpott Dam contains two galleries suitable for installation of tilt-monitoring mirrors. The upper gallery is approximately 100 feet long and runs immediately below the spillway section of the dam. This gallery was chosen for use in the test. Six mirrors were installed, two of the one-piece type and four of the two-piece type. On the downstream wall of the gallery, at a convenient height, two mirrors or each type were installed. Because tilt of the dam was expected, the mirrors were to be tested by comparing measurements to determine if all mirrors were tilting in the same manner. If all the mirrors agreed, any tilt found would be assumed to be in the dam, and the mirror mounts would be considered stable. Two mirrors of the second type were installed on the upstream wall of the gallery. If the dam tilted, the mirrors would give the same magnitude of tilt as those mounted on the downstream wall of the gallery, but the direction of tilt would be opposite. All the mirrors were mounted in the same monolith.

The mirrors were installed in the upper gallery during the last week of July 1981. Results of the tilt measurements through February 1982 are given in table 5. The first set of measurements (7/30/81) were taken immediately after installation of the mirrors, before the epoxy had cured, and are included only as a matter of record. Table 6 is of more significance because it shows the monthly changes in tilt recorded by the mirrors. The changes between 7/30/81 and 8/31/81 were quite erratic as would be expected, because the epoxy had not cured before the first set of readings. For the period 8/31/81 to 9/29/81, there was agreement between mirrors A, C, and D (mirrors A and B should have shown the same magnitude as, but a different sign from, mirrors C through E) while B, E, and F still gave erratic results. During the next period reasonable agreement was found for all mirrors except E. Finally, over the last two periods, good agreement was found for all the mirrors. Table 6 shows that between 9/29/81 and 11/17/81, the dam tilted downstream by approximately 31 arc seconds (disregarding mirror E); between 11/17/81 and 12/15/81, the tilt was an additional 19 arc seconds downstream; and finally between 12/15/81 and 2/18/82, the tilt had reversed and was 19 arc seconds in the upstream direction. The standard deviation of the last set of measurements was 2 arc seconds.

TABLE 5. Philpott Dam Tilt Measurements

DATE	POOL EL. (ft.)	GALLERY TEMP (C)	MIRROR A	MIRROR B	MIRROR C	MIRROR D	MIRROR E	MIRROR F
7/30/81	969	28	-13	-14	-11	-8	-70	-51
8/31/81	965	27	-15	-21	+13	-4	-37	-60
9/29/81	962	24	-22	-22	+24	+7	-51	-76
11/17/81	958	19	-58	-50	+54	+42	-59	-51
12/15/81	957	16	-80	-74	+67	+57	-40	-28
2/18/82	967	10	-63	-57	+48	+35	-59	-49

Mirrors A and B are on the upstream wall of the gallery.
Mirrors C, D, E, and F are on the downstream wall of the gallery.

TABLE 6. Differences in Tilt (Seconds)

BETWEEN	MIRROR A	MIRROR B	MIRROR C	MIRROR D	MIRROR E	MIRROR F
7/30 - 8/31	-2	-7	+24	-4	+33	-9
8/31 - 9/29	-7	-1	+11	+11	-14	-16
9/29 - 11/17	-36	-28	+30	+35	-8	+25
11/17 - 12/15	-22	-24	+13	+15	+19	+23
12/15 - 2/18/82	+17	+17	-19	-22	-19	-21

Mirrors A and B are on the upstream wall of the gallery.
Mirrors C, D, E, and F are on the downstream wall of the gallery.

One other brief field test with the tilt-monitoring system was performed during a visit to Holt Lock and Dam in the Mobile District on 18 May 1981. The calibration mirror was set up on the land side of the lock, midway between the lock gates, with the plane of the mirror parallel with the axis of the lock wall. The weather was slightly hazy, with sun. The mirror was shielded by an umbrella to reduce thermally induced changes in the tilt of the mirror.

At the time the first measurement was made, the lock had been empty for about one hour. Immediately afterwards, a ship locked through and then the lock was again emptied. Table 7 shows the results of measurements made at the time.

A set of readings made during the course of a demonstration showed a tilt of about 3 arc seconds for a gate monolith during a similar empty-fill-empty cycle.

TABLE 7. Lock Measurements

TIME	**LOCK CONDITION**	**READING (seconds)**
1550	Empty for one hour	+54.2
1557	Half full	+55.1
1605	Full	+52.7
1630	Empty	+63.3
1645	Empty	+63.5
1700	Empty	+63.4
1730	Empty	+63.3

Increasing readings mean tilt of the top of the lock wall in the direction of the center of the lock.