INCLINOMETERS

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INCLINOMETERS

Introduction - An inclinometer is an instrument, which is used to measures ground movements. This instrument measures ground movements in directions perpendicular to the axis of a drill hole where a grooved casing has been installed. An inclinometer monitors horizontal movements in near vertical drill holes and through the use of data reduction programs can provide a complete and detailed profile of displacements along the drill hole. This detailed profile will give localized ground movements wherever they occur. An inclinometer system for measuring these detailed profiles consists of a probe fitted with guide wheels and containing biaxial gravity-operated tilt sensor connected by an electrical cable to a power source and readout unit.

For obtaining horizontal ground movements at only selected locations within a drill hole, a fixed-in-place inclinometer is used. A fixed-in-place inclinometer consists of a series of probes fitted with guide wheels and each containing a biaxial gravity-operated tilt sensor. The probes are joined by articulated rods and suspended down a guide casing within the drill hole. Electrical cables connect each sensor to the ground surface where they are attached to a power supply and readout unit. The in-place inclinometer can provide ground movement information perpendicular to the drill hole axis at the depths selected where the probe is set with the guide casing. The in-place inclinometer will provide continuous information about that selected depth in the guide casing. These instruments may be automated or an alarm can be added to the unit if required.

Below is a list of manufacturers who make inclinometer equipment and or inclinometer accessory equipment throughout the world.

INCLINOMETER MANUFACTURERS

Country	**Company**	**Type of Instrument***
USA		
	Geo-Testing, CA	A
	Applied Geomechanic, CA	A
	Slope Indicator Company, WA	A, P
	Geokon Inc., NH	A
	Terra Technology Inc., WA	A
CANADA		
	Solinst, LTD., ON	A
	Westbay, Inc., BC	A

INCLINOMETER MANUFACTURERS

Country	Company	Type of Instrument*
EUROPE		
	Geonor, Norway	V, A
	Geotechnical Instruments, UK	A
	Glotzl, Germany	A
	Maihak, Germany	V
	Soil Instruments, LTD, UK	A, S
	Telemac, France	V
	Huggenberger, Switzerland	S
	SolExperts LTD, Switzerland	S
JAPAN		
	OYO, Tokyo	A, S

*Instrument Types
A- Servo-accelerometers, P - Pendulum, S - Strain Gauge,
V - Vibrating wire

From the above list of manufacturers we have had experience with the equipment manufactured by Slope Indicator Company, Terra Technology, Inc., Geokon, Inc., and Soil Instruments, LTD. Since inclinometer equipment is very expensive to purchase and requires a lot of manpower to collect and reduce the data, the usage of this type of instrument is limited.

Inclinometers are probably the most difficult instrument that we use when it comes to collecting and reducing data. A number of advancements have taken place in our section and by the instrument manufacturer when it comes to the collection and reduction of this kind of data. Even with these advancements it can still come down to understanding how the instrument works to be able to review the data correctly. In the following discussion I will attempt to explain how the instrument works and how the data can be reviewed.

Bureau's Use of Inclinometers
The Bureau has used inclinometers to monitor the movements of the following features:

1) To monitor landslides at dams (horizontal movements)
BF Sisk, Costilla, El Vado, Fruitgrowers, Guajataca, Jordanelle, Lake Sherburne, Lewiston (Baker's Gulch), Mt. Elbert, Ochoco, O'Neill, Palisades, Red Fleet, Ridgway, Scoggins, and Trinity.

2) To monitor embankment and concrete dam movements (settlements and horizontal deflection) Batu, Brantley, Calamus, Davis Creek, Diamond Creek, Fontenelle, McGee Creek, McPhee, Morman Island, Navajo, New Melones, New Wadell, Palmetto Bend, Ridgway, Ririe, T. Roosevelt, San Justo, Steinaker, Sugar Pine, Trenton, and Upper Stillwater.

3) To monitor structures (outlet works, canals, etc.) Currant Creek, Meeks Cabin, Delta Mendota Canal, West Fork Pipeline, and West Fork Highway.

Below is a table that lists all the dams that we are using inclinometers at presently or have used at in the past. The table is mainly for information about a given dam and information concerning a given instrument at that dam. The table lists the model number of the sensor, serial number, and the sensor's range of measurement.

BUREAU DAMS USING INCLINOMETERS

DAM	MODEL NO.	SERIAL NO.	RANGE
Batu	Unknown	Unknown	30
B.F. Sisk	50323E	Unknown	30
B.F. Sisk	In-Place	Many	30
Brantley	50325E	Unknown	30
Calamus	50325E	25525	30
Calamus	50325E	25527	30
Costilla	50325E	25504	30
Currant Creek	200-B	Unknown	30
Davis Creek	50325E	25525	30
Diamond Creek	50325E	Unknown	30
El Vado	50325E	Contractor	30
Fontenelle	50325E	Unknown	30
Fruitgrowers	50325E	25674	90
Guajataca	Unknown	Unknown	30
Jordanelle	503025	26610B	90
Lake Sherburne	TPC-20	225	30
Lewiston	50325E	25305	30

DAM	MODEL NO.	SERIAL NO.	RANGE

McGee Creek	50325E	25721	30
McPhee	50325E	27117B	30
Meeks Cabin	200-B	Unknown	30
Morman Island	50325E	25480	30
Mt. Elbert	50320	20137	30
Navajo	50325E	25794	90
Navajo	TPC-20	227	30
New Melones	50325E	25480	30
New Wadell	50325E	Unknown	30
Ochoco	50325E	25504	30
O'Neill Forebay	50325E	25480	30
Palmetto Bend	50325E	25243	30
Palisades	50325E	Unknown	30
Red Fleet	50325E	25142	30
Ridgway	50325E	25308	30
Ridgway	50325E	25674	30
Ririe	50320	Unknown	30
Rye Patch	50325E	27496B	30
San Justo	50325E	25974	30
Scoggins	50325E	26677B	30
Steinaker	50325E	25142	30
Steinaker	In-Place	Many	30
Sugar Pine	50325E	25480	30
Trenton	In-Place	Many	30
Trinity	50325E	25305	30

Instrument Accuracies - The over all inclinometer system needs to be reviewed as to the accuracies of each installation and sometimes as to the spiral or twist within the drill hole of the inclinometer casing itself. The manufacturer of the inclinometer instrument and casing has provided some general accuracies of their equipment and casings. The accuracies are general guidelines and can be improved upon by good data collection policies. Each inclinometer drill hole installation should be viewed as to having its own accuracies and only use the following as guidelines. The inclinometer has the following accuracies defined:

(1) System accuracy of +/- 0.025 feet per 100 feet, with a resolution of .0001 feet per 2 feet, and a repeatability of +/- 0.01% full scale.

(2) Smallest change in inclination angle that can be detected, corresponding to one digit, is approximately equivalent to one part in 10,000 or about 10 seconds of arc at 0E inclination.

(3) Spiral of plastic ABS casing of # 1/3E per 10 feet of casing, or 3.3E per 100 feet depth; spiral of EPIC plastic ABS casing # 1/2E per 10 feet of casing, or 5E per 100 feet depth; and spiral of aluminum casing # 1E per 10 feet of casing, or 10E per 100 feet depth.

The accuracy of any given installation can be determine by reviewing of the data over repeated measurements and comparing the repeatability of data sets and the standard deviation of each data set. Each casing should have a standard deviation of both the A and B axis determined and each set of data taken should fall near this standard. A typical standard deviation for the A axis is less than 10 and a typical standard deviation for the B axis is twice the A axis. The B axis is always larger than the A axis since the B axis is not set in the instruments sensitive movement direction.

Total Measurable Movements - The inclinometer casing, which is installed with in a drill hole or an embankment during construction, is going to move over the life of the instrument. How much movements will the casing take before it becomes blocked has always been a matter of opinion. The casing type and diameter of the casing is very important when it comes to the maximum movement that will be measured. The type of movement as to an abrupt shear verses a large mast moving makes a difference. The following are some general guidelines for movements that have been measured at different projects.

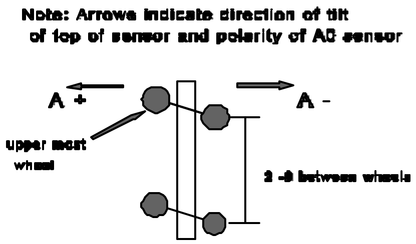
MAXIMUM INCLINOMETER CASING MOVEMENTS

Dam	Casing Diameter	Casing Type	Hole Diameter	Measured Movement
BF Sisk	3.38"	Aluminum	6-inches	6 to 8-inches
McPhee	2.75"	Aluminum	4-inches	2.4-inches
Muddy Creek	1.90"	Plastic	3-inches	1-inch
Red Fleet	2.75"	Aluminum	4-inches	1.8-inches
Steinaker	2.75"	Plastic	4-inches	2.1-inches
Ochoco	2.75"	Plastic	4-inches	2.9-inches

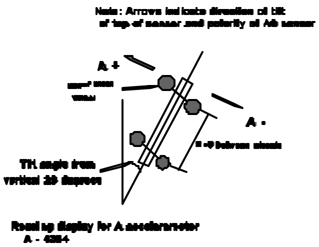
As you can see from the above table, the movements measured can vary according to the site conditions where the casing is installed. If there is a small shear plane as in the case at Red Fleet Dam, the movements did not even reach the inside diameter of the casing. With a large mast movements, the measured movements can be twice the inside diameter of the casing or more.

How the Inclinometer Works - The inclinometer is an electronic instrument that measures the averaged horizontal movement of a vertical casing usually installed within the ground. The inclinometer consists of four pieces of equipment, the grooved casing, the inclinometer probe, the inclinometer cable, and the inclinometer readout. The inclinometer is read by an operator moving the probe within the casing and storing the data on either on a data sheet, on a magnetic tape, or within the memory of a data-recording device. The readings being recorded or stored are the DC voltage from the inclinometer probe as it travels within the casing. These DC voltage readings come from two closed-looped, servo-accelerometers contained within the probe. These accelerometers are set at right angles to each other. The input to the accelerometer is ∀ 12 Volts DC provided by the readout unit. The output of the accelerometer is a DC voltage, which varies proportionally to the sine of the angle from a vertical plane. The accelerometers have an acceleration input range of ∀ 0.5 g that occurs at an angle of 30E from the vertical plane. One

`Figure 1`

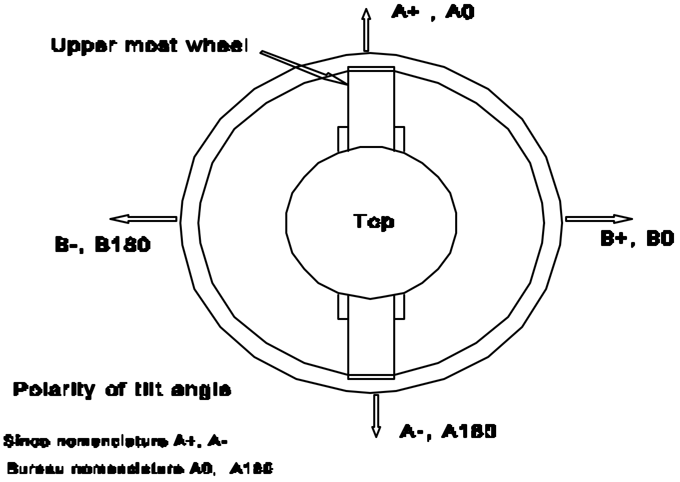


accelerometer is set parallel to the tracking wheels (A+ direction) of the probe and other is set perpendicular to the wheels (B+ direction). The accelerometer reads in both positive and negative directions according to which direction the accelerometers are positioned. The positive direction of the A accelerometer is aligned to the upper most wheel of the wheel assembly of the probe (Figure 1). The positive direction of the B accelerometer is positioned 90E clockwise to the A position (Figure 2). These accelerometers are set in the probe at the factory and can't be adjusted.



The actual data reading from the accelerometers is the voltage required to force the accelerometer at a certain angle from vertical within the casing, back to its vertical position. This reading has a polarity sign indicating if the probe is tilting in a positive or negative direction from vertical. The readings should be used as whole numbers, ignoring the decimal point on the readout unit (the actual meter reading is equal to 2 sine) (Figure 3).

Figure 3



For maximum accuracy, two sets of readings are taken by rotating the borehole probe 180E so that the spring-loaded wheels travel in opposite grooves of the casing. This process will eliminate or minimize errors contributed by casing irregularities, depth measurements, and instrument calibrations. The inclinometer does not measure displacement directly. Instead, it measures the tilt of the casing. The tilt is converted to a lateral distance as shown in figure 3. As you see this data reduction can be very time consuming and should be done by a computer. There are a number of computer programs available that can reduce the data and also plot the results. Another option that requires the use of computer data reduction is the use of spiral or twisting of the casing within the drill hole. The spiral can be measured with a spiral probe and the inclinometer deflection data can be corrected for this spiral. The use a of spiral probe is only required if the inclinometer casing is showing movements in a direction that is not expected. Most casing installations do not require this spiral data to be collected, but if necessary this spiral survey is only required to be taken once per casing installation.

Hints for Better Data - **For the highest accuracy, always use the same probe and control cable. If you must use different probes, be sure to note the serial number of**

the probe used for each data set so corrections can be made during data processing.

Always use the same reference for the depth marks on the control cable. If one technician uses the cleat on the pulley assembly as reference and another technician uses the top of the casing as reference, there will be a one-foot variation in the probe position from survey to survey. Accurate results require placement repeatability of 1/4-inch or better.

Mark the A0 groove with paint or with a notch in the casing. Always start the survey by placing the top wheels of the probe in that groove. Training of technicians should include the importance of starting with the probe in the correct orientation.

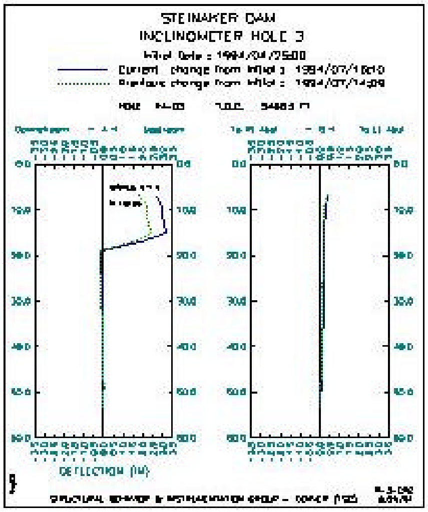
It is recommend that a new installation be surveyed two to three times and the checksum statistics for each set be compared. Choose a representative set as the initial reading set. All other data sets will be compared with this set.

Two problems that can occur with inclinometer data are, instrument zero shift and a rotation error. Instrument zero shift is caused by electrical inaccuracies within the sensor and is corrected by averaging readings. In holes that are nearly vertical, the zero shift is sufficient. If the hole is inclined 3E or more, than relative rotation shifts will cause an error and can’t be corrected by opposite readings. Therefore the installation of an inclinometer casing requires a drill hole that is near vertical and collection of data in both the A0 and A180 directions. The rotation error can also be introduced whenever a inclinometer sensor is interchanged with another sensor or the sensor is repaired. During manufacturing, it is virtually impossible to adjust and control the sensitive axis of the sensor closer than ∀ 1/2 E from nominal. If two different sensors would typically be used to collect data a relative rotation of the sensitive axis would be in the range of 1E. This interchanging of sensors should be avoided. Repair or replacement of an accelerometer within the probe could have a relative rotation of sensitive axis within a 1-degree range when compared to data recorded prior to the repair. Rough handling can also be responsible for the introduction of rotation errors.

<u>Data Reduction Within Our Office</u> - The inclinometer readings are reduced once the data has been entered in the correct format on a UNIX system. The readings as we receive them are the raw voltage readings. Once the data has been reduced as described above, the movements are plotted to better understand the large amounts of data processed. To the Right in figure 4, is a plot of data from Steinaker Dam.

The plot shows the changes in profiles of both the A and B axis compared to an initial date and a previous date. The movements are shown in inches but could be any unit of measure necessary. These changes are from the profile of both the A and B axis as they are calculated summing from the bottom of the hole to the top. The profiles are calculated and the changes are calculated in either the plus or minus direction and then plotted.

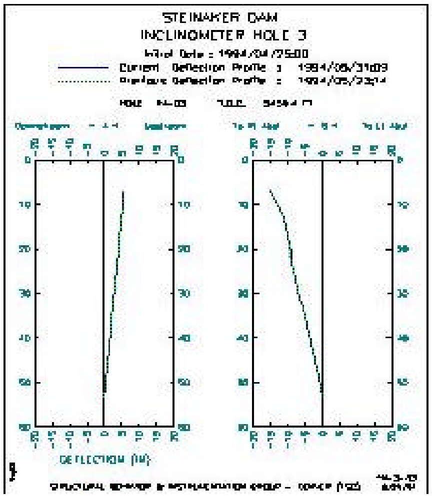
Figure 4



The measurements that were taken in this drill hole show a movement occurring at a depth of 15 feet below the top of the casing. This movement is occurring in an upstream direction again based on the initial survey taken in the casing. This initial survey is very important and should be taken at least twice with the data being averaged to obtain one set of readings. The initial readings should be taken as soon as the grout backfill in the drill hole has cured. The two sets of data should be taken within hours of each other so that no ground movements will effect your readings. All future readings in a casing are compared to this initial reading.

Another plot of data that is used shows the actual profile of a casing from vertical. This profile is the summing of each position measured or depth reading from the bottom of the hole to the top (Figure 5).

Figure 5



The calculation used to determine the deflection from vertical for a **Slope Indicator 30E** probe is the following: the readings are proportional to the angle of tilt and are display by readout units as sin X 20,000. Eliminating the decimal point from the reading, use the digital voltmeter reading making a full-scale reading of ∀ 5,000 equal to sine of the angle of ∀ 30E for full scale. Taking the algebraic different for both the A and the B directions at each depth or the A0 and A180, B0 and B180 and then multiplying this difference by 6 times 10^{-4}. The sign of any number is determined by this summing calculation, and usually the sign of the A0 and B0 readings determines the sign or direction of the movement (i.e. uphill or downhill). This overall calculation gives you a reduced value in inches from vertical for a given depth. This value is then added to the reduced value of the proceeding depth or the values are summed from the bottom of the hole to the top. This summing is done for both the A and the B directions. The values stored in the database are the these summed values or the position of each depth reading from vertical.

All data are compared to an initial set of readings and to the previous set of readings. Below is a listing showing the report that is generated when an inclinometer data file is processed.

Dam: Ochoco Reported by:
Inclinometer Hole: IN-01 Set: 0 (D-3621) rdavis
Date: 1994/06/22;08 Wed Jun 22 10:53:36 MDT 1994
Slope Indicator RPP - 30 Degree **<- Instrument type**
Elevation Top of Casing: 3091.70 Bearing of +A Axis: S 02 W

A - Axis Orientation	B - Axis Orientation
+ Indicates Deflection Along Survey Bearing	+ Indicates Deflection in Direction 90 Degrees from +A Axis
A0 direction	**B0 direction 90E clockwise**

Depth	DEFLECTION FROM VERTICAL **Summing from bottom of hole**	CHANGE FROM INITIAL	CHANGE FROM PREVIOUS 1994/06/21	DEFLECTION FROM VERTICAL **Summing from bottom of hole**	CHANGE FROM INITIAL	CHANGE FROM PREVIOUS 1994/06/21
				Top area of hole.		
2.0	-23.324	0.491	0.033	-72.235	-0.543	-0.026
4.0	-22.788	0.512	0.031	-70.880	-0.541	-0.024
6.0	-22.288	0.528	0.029	-69.526	-0.533	-0.020
8.0	-21.896	0.543	0.027	-68.197	-0.525	-0.020
10.0	-21.725	0.567	0.027	-67.025	-0.507	-0.019

Bottom area of hole.

```
Depth
90.0    -3.185    -0.001   0.005    -8.191    -0.021    -0.007
92.0    -2.617     0.000   0.004    -6.493    -0.016    -0.005
94.0    -1.983     0.002   0.004    -4.740    -0.017    -0.004
96.0    -1.330     0.000   0.002    -3.036    -0.012    -0.003
98.0    -0.685    -0.002   0.000    -1.425    -0.014    -0.002
100.0    0.000     0.000   0.000     0.000     0.000     0.000

Slope Indicator Raw Values are in .0001 Feet.     <- This area has to
Terra Probe Raw Values are in .001 Inches.           do with the mean
Allowable Values are Within 25 Least Digits          and standard
Plus or Minus From the Mean.                        deviation below
Dam: Ochoco   Date: 1994/06/22;08                    based on raw values
Hole:  IN-01    Set: 0
**********  A Direction  **********
    12.1  Mean                   <- The mean value is calculated on the raw valves
     5.9  Standard Deviation     <- Calculated with the raw values
**********  B Direction  **********
    19.6  Mean                   <- The mean value is calculated on the raw valves
     8.3  Standard Deviation     <- Calculated with the raw values
```

In reviewing the comparison data sheet above, you can see that very little change has taken place near the bottom of the hole from the previous or initial data sets. At the top of the hole larger movements are taking place. At a 2-foot depth, changes in the B direction are -.543 from the initial and -.026 from the previous date. The movements are changes from the original and previous locations of the casing at 2-foot depth intervals with the changes indicated in inches. Since these changes are negative, the movements would be 180E from the know B axis direction.

Validity of the data is checked in the program and shown on the second page of the comparison sheet above. The data is checked for both the A and B axis. This validity is accomplished by adding the opposite readings obtained at each depth, i.e. A0 added to A180, B0 added to B180. The results are called the checksum and should remain with ∀ 25 digits of zero. The mean of all checksums for that data set is also calculated. Ideally, the mean checksum would be zero, but that is usually not possible. The mean checksum is used more to evaluate the inclinometer probe itself than to evaluate a data set. The mean checksum indicates the probable zero offset for the inclinometer probe. Typically, the mean checksum is less than 50. Large offsets (larger than 100) may mean a damaged probe. The standard deviation of the check sum is also calculated. The standard deviation provides the surest way of validating a data set. Future comparisons of the standard deviations indicate how the inclinometer probe is performing. If the standard deviation is slowly increasing over a number of inclinometer surveys than the probe may be in need of repair. Compare standard deviations of a typical set of data to the initial set of statistics. If the standard deviation is 3 to 5 units of typical, the data are probably good. Wider limits may be appropriate for shallower installations or for poorly installed casings.

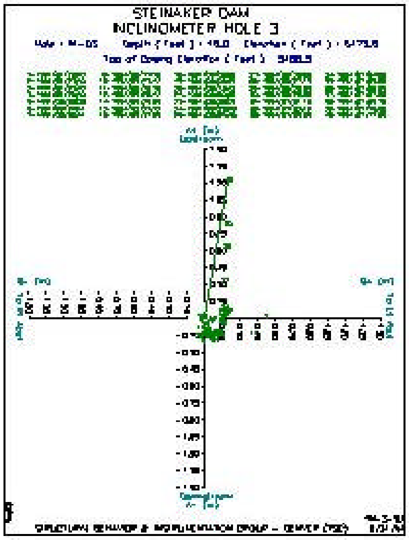
Data Review.- Plots that we use in the review of the inclinometer data are shown in the following figures:

1. **Profile of Changes** plot showing comparisons (Figure 4) see page 9. This change plot shows the movement of both the A and B axis compared to the initial survey. This plot shows changes based on the centerline of each plot being the initial survey and the lines represent the changes taking place. The plot shows a current survey date and a previous date, both dates are compared to the initial survey. Both the A axis and B axis are shown on this plot. All movements are shown in inches but any other unit of measure could be used as is with all the plots in the following paragraphs.

2. **Actual Profile** plot showing actual location profile (Figure 5) see page 10. The actual profile plot shows the actual profile of both the A and B axis of the casing. This profile is calculated by summing up each depth position in the hole from the bottom of the hole to the top. Both the A axis and the B axis are show on this plot.

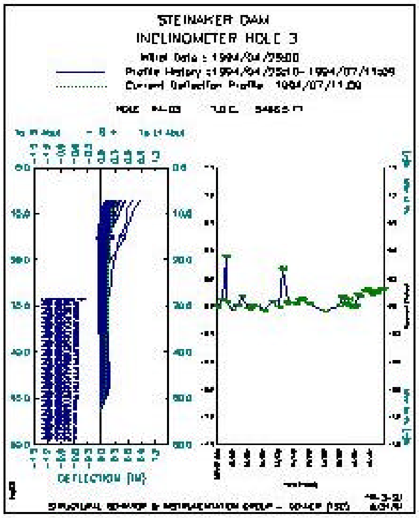
3. **Slice** plot showing a depth of a casing (Figure 6). The slice plot shows a cross section of a casing at a chosen depth. If you take a depth within the casing and slice the casing, the plot shows this depth and its movements. The plot presents all four directions of the casing and the history of the movements that have taken place over time at this depth. The numbers that are plotted indicates the dates and these numbers can be referenced to the dates shown near the top of the page. The initial location of the casing at this depth is the origin of the X and Y-axis. The movements that have occurred at this depth are shown moving from that origin point. As you can see, this casing is moving upstream and to the left abutment at a depth of 15 feet or an elevation of 5473.5. The last survey taken of this casing which was taken on July 11, 1994, is indicating a total movement of 1.25-inches upstream and can be located on the plot by following the line from the origin to the last survey date (number 40). A total of ten depths can be selected and plotted on individual plots like this one. This type of plot is very helpful if there are many depths where movements are occurring, these movements can be followed, vectors can be determined and the rates of movement over time can be observed. The plot allows for either changes from the initial survey to be plotted or the

Figure 6



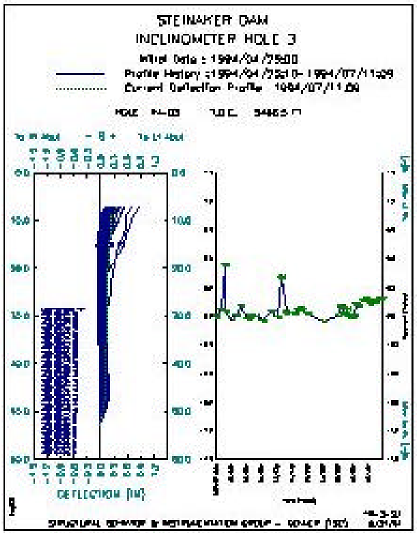
actual deflection from vertical can be plotted in a similar manner.

Figure 7



4. **Multi-plot A** axis showing multiple profiles of the A axis and one selected depth verses time (Figure 7). Multi-plot shows a multiple number of profiles indicating changes from the initial survey as shown in figure 4 with the following exceptions. The profile history on the left side of the plot, is of the A axis and is given over a range of time that can be selected. On the right side of the plot is the change from the initial survey at a selected depth verses time. This selected depth is the same depth selected in the slice plot of figure 6. A total of ten depths can be selected and plotted on this depth verse time plot on the right side of figure 7.

Figure 8

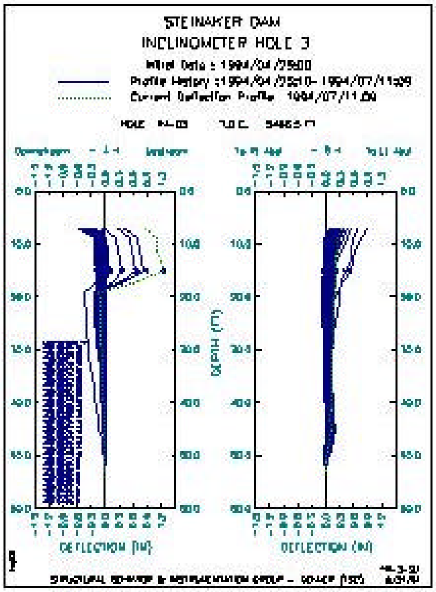


5. **Multi-plot B** axis showing multiple profiles of the B axis and one selected depth verses time (Figure 8). Multi-plot shows a multiple number of profiles indicating changes from the initial survey as shown in figure 4 with the following exceptions. The profile history on the left side of the plot, is of the B axis and is given over a range of time that can be selected. On the right side of the plot is the change from the initial survey at a selected depth verses time. This selected depth is the same depth selected in the slice plot of figure 6. A total of ten depths can be selected and plotted on this depth verse time plot on the right side of figure 8.

6. **Multi-plot A and B** axes showing multiple profiles of both the A and B axis (Figure 9). Multi-plot shows a multiple number of profiles indicating changes from the initial survey as shown in figure 4 The profile history on the left side of the plot, is of the A axis while the profile history on the right side of the plot is of the B axis. The histories are given over a range of time that can be selected. We have limited our date range to 30 dates since more dates than 30 would have a tendency to confusion the plot unnecessary.

From the review of the six previous plots, it is clear where the movements were occurring in this inclinometer casing. After reviewing the drill log of this hole, the material where the casing is moving at, a depth of 15 feet is an embankment material with fat clays. This material moved upstream into the reservoir at this depth because of an abnormally low reservoir level because of downstream construction taking place.

Figure 9



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