Landslides
DOI 10.1007/s10346-008-0126-3
Received: 21 August 2006
Accepted: 26 July 2007

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Slope inclinometers for landslides

Abstract Slope inclinometers/indicators are used to determine the magnitude, rate, direction, depth, and type of landslide movement. This information is usually vitally important for understanding the cause, behavior, and remediation of a landslide. However, many inclinometer measurements fail to achieve these intended aims because of lack of appreciation of the many factors that need to be correctly implemented during installation, monitoring, and data reduction to yield useful data. This paper presents some guidelines for understanding, installing, and interpreting slope inclinometers and presents three case histories that illustrate some of the pitfalls that can develop if these guidelines are not followed.

Keywords Slope stability · Instrumentation · Landslides · Slope inclinometer · Failure plane

Introduction

The slope inclinometer commonly used today is derived from a prototype built in 1952 by Stanley D. Wilson. The inclinometer first became commercially available in the late 1950s from the Slope Indicator Company which Stan Wilson founded (Green and Mikkelsen 1986, 1988). A slope inclinometer is a device for monitoring the onset and continuation of deformation normal to the axis of the borehole casing by passing a probe along the casing (Dunnicliff 1988). Thus, an inclinometer monitors deformation normal to the axis of the casing which provides a profile of subsurface horizontal deformation. The depth at which shear movement is detected by the slope inclinometer is the depth of the failure surface. The portions of the casing that have not sheared represent the areas above and below the failure surface if there is one failure plane impacting the casing.

The inclinometer probe contains at least one, if not two, force-balanced servo-accelerometers that measure the inclination of the casing with respect to the vertical. If one accelerometer is used, the probe is called a uniaxial probe, and four passes of the probe are required to measure the tilt of the casing in the four different directions of movement (A0, A180, B0, and B180 directions which are discussed subsequently). The commonly used probe is a biaxial probe which contains two perpendicular accelerometers, so only two passes of the probe are required to measure movement in the four different directions. One accelerometer measures the tilt in the plane of the inclinometer wheels which tracks the longitudinal grove of the casing, while the other accelerometer measures the tilt in the plane perpendicular to the wheels. Thus, in a biaxial probe, the A-sensor is oriented to the A direction which is parallel to the wheels of the probe, and the B-sensor is oriented transverse to the wheels in the probe. This paper focuses on the use of a biaxial probe.

Figure 1 shows the probe in the casing and the inclination of the casing at every measuring point, θ, with respect to the vertical. The inclinometer probe is connected to a power source and readout unit to enable measurements. The electrical cable linking the probe to the readout device is usually marked in 0.3 or 0.6-m increments so the shape of the casing can be measured at consistent depths or locations. The measurements are taken starting at the bottom of the inclinometer. Subsequent readings are made of the casing as the probe is raised incrementally, usually in 0.3 or 0.6-m intervals, to the top of the casing. This process is conducted shortly after the casing is installed to determine the initial shape of the casing, i.e., obtain the zero reading. The difference between the zero and subsequent readings is used to determine the change in the shape and position of the initially vertical casing (Terzaghi and Peck 1967). As a landslide moves, the vertical casing moves in the direction of landsliding. Comparison of the verticality of the casing with time and width of the slide provides an insight to the magnitude, rate, direction, depth, and type of the landslide movement.

Installation and monitoring of inclinometers

The slope inclinometer installation and interpretation processes involve several important factors or steps so the resulting measurements and difference between the zero and subsequent readings are meaningful. First, the bottom of the inclinometer must be located well below the potential zone of movement so the bottom of the inclinometer does not translate. If the inclinometer is not located well below the zone of movement, the inclinometer will not capture the total amount of movement. In other words, the inclinometer that is too shallow can yield too small of a movement, if any, when compared to sufficiently deep inclinometers. This discrepancy can lead to confusion about the type, size, and shape of the slide mass, and/or the magnitude and rate of movement of the slide, as will be illustrated in one of the case histories described at the end of the paper. Second, the same probe and electrical cable used for the zero reading should be used for subsequent readings so all of the readings are comparable to the zero reading. It is also preferable that the same person performs all of the readings so the results do not have any bias or unwarranted differences from the zero reading. These consistencies are important because the magnitude of movement, rate of movement, and direction of movement are derived from the difference between the zero and subsequent readings, so using the same equipment, and ideally the same operator, is critical to make this comparison meaningful. If different probes are used, the sensors can/will have different sensitivities, zero voltages, and calibration factors that can result in the appearance of a different inclination or shape of the casing. In addition, the same electrical cable should be used so that the probe readings are taken at the same depth as the zero reading so the deflection is determined at the same depth. Unfortunately, in practice, it is common for one entity to install and start measuring the slope inclinometer casings for a period of time. For some reason(s), another entity is then retained to measure the casings

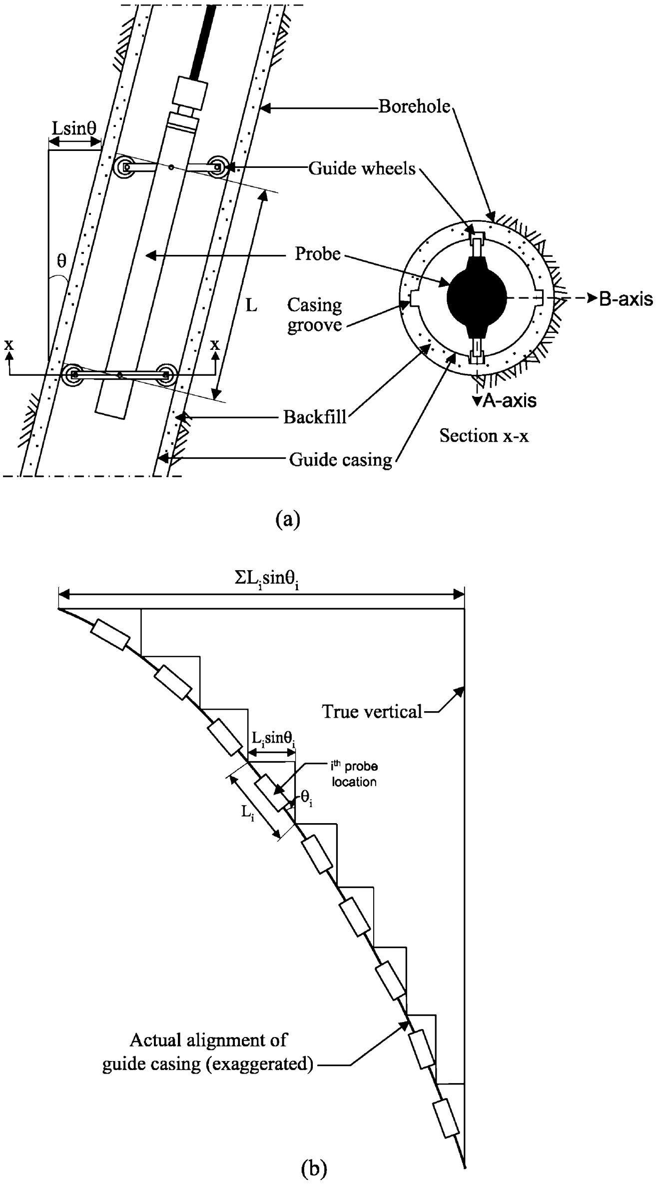

Fig. 1 **a** Principles of inclinometer configuration of inclinometer equipments. **b** Illustration of inclinometer operation (modified from Dunnicliff 1988 and Slope Indicator 2005)

usually with their probe instead of the initial probe. If litigation develops, the causation expert has to try to combine the data from the two or more different probes and operators. This is frequently difficult to impossible because the zero readings for each probe and depths of the readings are usually different. This makes determining the magnitude, rate, and direction of cumulative movement difficult and extremely time consuming, if not practically impossible during the rigors of litigation (ASTM D 7299 2007).

Many inclinometer projects fail to achieve the intended aim because of lack of appreciation of the many factors that need to be correctly implemented during installation, monitoring, and data reduction (Green and Mikkelsen 1986). The precision of inclinometer measurement is limited both by the sensitivity of the inclinometer probe and by the reading operations that require successive readings with the same orientation of the instrument at the same depth in the casing. Factors affecting the proper interpretation of the results and precision of the inclinometer measurements are described in the following sections.

Importance of slope inclinometer data

Magnitude and location of movement

The inclinometer probe does not provide horizontal movement of the casing directly. As shown in Fig. 1, the probe measures the tilt of the casing which can be converted to a horizontal movement. In Fig. 1, the angle θ is the angle of tilt measured by the inclinometer probe, and L is the measurement interval. The measurement interval is recommended to be the distance between the probe wheel carriages to achieve the maximum precision as shown in Fig. 1a. If the measurement interval is greater than the length of the wheelbase, deformation profiles of the casing are not smooth enough to obtain the required precision. A greater interval may sometimes be used with little loss of accuracy if thin shear zones do not exist (Dunnicliff 1988; Green and Mikkelsen 1988). This discussion highlights the importance of using the same probe and same measurement depths so subsequent values of tilt, i.e., horizontal movement, can be compared because the tilt is a function of the measurement interval.

The deviation from vertical, i.e., horizontal displacement, is determined by the sine function and expressed as follows:

$$\text{Deviation from vertical} = L \times \sin\theta \qquad (1)$$

The vertical deviation at each measurement interval is the lateral position of the casing relative to the bottom of the casing because the bottom of the casing remains fixed and does not move laterally. The deviation values can be plotted as an incremental displacement or slope change profile (i.e., slope change vs. depth) to show movement at each measurement interval. The incremental displacement profile is useful to dramatize the location of the deformation zone. A spike in this plot indicates the location of movement, i.e., the failure plane (see Fig. 2a).

Integration of the slope change, i.e., deviation, between any two measurement points yields the relative deflection between these points. The total horizontal displacement, i.e., cumulative displacement, profile of the casing is achieved by summing the individual lateral deviations from the bottom of the casing to the top. This summation process is described in Fig. 1b and is shown as $\Sigma L_i \sin\theta_i$ in Fig. 1b. The cumulative horizontal displacement profile (see Fig. 2b) provides a representation of the actual deformation pattern (Dunnicliff 1988).

It is often difficult to determine the zone of movement within a sliding mass from undisturbed samples. As a result, the incremental deflection and cumulative horizontal displacement profiles shown in Fig. 2 are usually the most reliable means to determine the zone of shear movement. The cumulative displacement from inclinometers installed across the width of the slide mass should be plotted on a plan view of the slide mass with time to investigate the geometry of the slide mass. This plot also indicates which portion of the slide mass is moving the fastest. This plot also helps determine the limits of the slide mass.

Rate of movement

Another purpose of inclinometer measurements is to determine the rate of shear movement. The rate of movement is frequently more important than the magnitude of movement because it

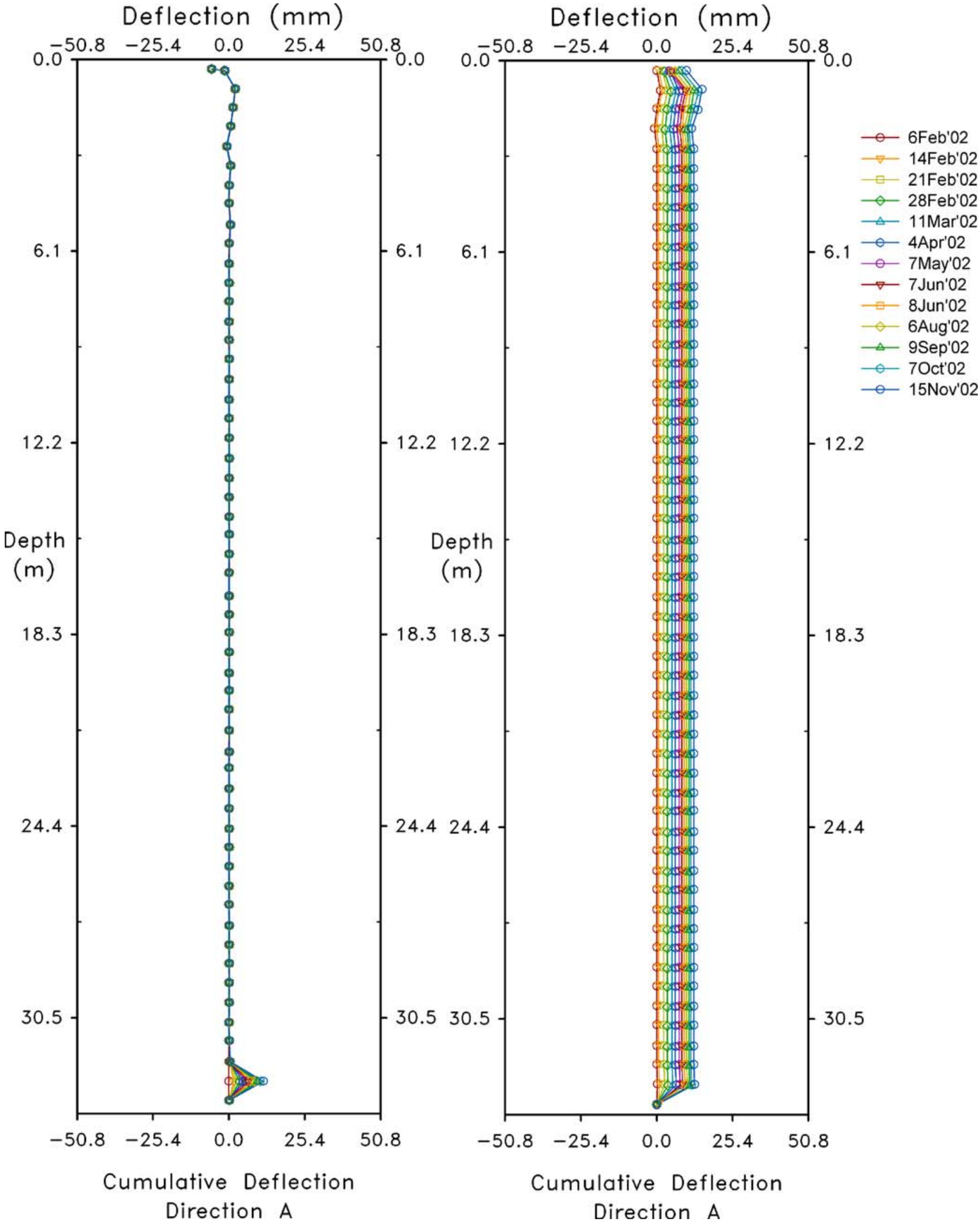

Fig. 2 Example of inclinometer data (I-1 in case no. 3) plotted in terms of **a** incremental displacement and **b** cumulative deflection

determines whether or not the slide is accelerating, decelerating, or continuing at the same rate. Of course, if the slide is accelerating or even maintaining the same rate, evacuation of the affected area should be considered. If the slide is slowing, evacuation may not be necessary and remedial measures may be possible. The rate of movement can be assessed from a plot of cumulative displacement versus time data as shown in Fig. 3.

Whether the slide is accelerating or moving at the same rate is also important to determine shear strength and potential for strength loss. For example, if the shear zone is not at residual strength, strength loss will occur with continued movement until the residual condition is reached. This strength loss phenomenon can result in acceleration of the slide mass and progressive failure of the slope (Skempton 1985). The rate of movement is also of importance to investigate the effect of rainfall, slope loading, toe excavation, and remedial measures on slope stability.

The displacement vs. time profile at a specific depth interval is useful to determine the rate of movement at that depth. This profile is shown in Fig. 3 and shows the change in cumulative movement with time. Once detecting the active shear zone, the rate of movement can be determined by plotting the cumulative displacement vs. time. Usually, the shear zone is less than a few meters thick, and thus the sum of change over this zone is representative of the magnitude and rate of the entire landslide (Mikkelsen 1996). An increasing slope of the cumulative displacement vs. time relationship represents an accelerating movement, a decreasing slope represents a decelerating slope, and no slope change represents movement at the same rate.

Direction of movement

Determining the direction of movement is important because the critical cross-section should be parallel to the direction of movement. Knowing the direction of movement can reduce the number of cross-sections that need to be considered in the stability analyses and remedial design because the various cross-sections should be parallel to the direction of movement. Locating the critical cross-section is important for determining causation, back calculation of shear strength parameters, and design of remedial measures. The direction of movement can also be used to determine if the slide is moving as a single unit or not, which can facilitate determining causation and remediation.

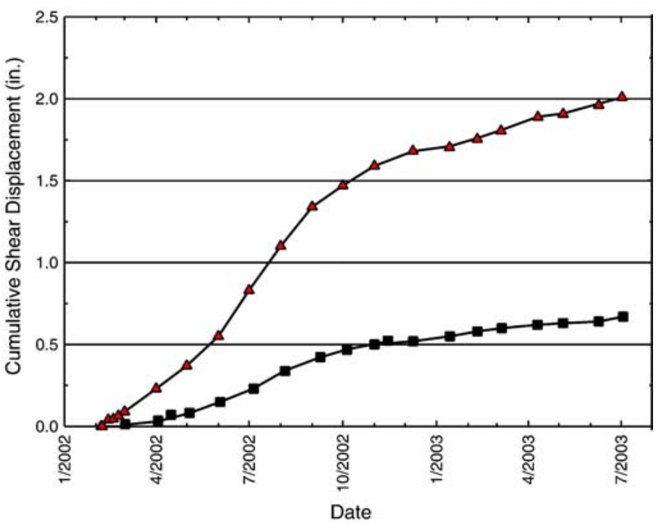

Fig. 3 Example of inclinometer data plotted in terms of displacement versus time

The horizontal displacement profiles of the casing are usually determined using the data from the A- and B-axes of the inclinometer casing. These axes are mutually perpendicular vertical planes as shown in Fig. 1a. The A-axis is usually oriented in the direction of slide movement during installation of the casing. These two axes are equipped for the use of two sensors (A and B sensors) in a biaxial probe (i.e., biaxial sensors) that is commonly used in practice.

Two sets of casing grooves allow the inclinometer probe to be oriented in either of two planes set at 90° to each other. Thus, horizontal components of movement, both transverse and parallel to any assumed direction of sliding, can be computed from the inclinometer measurements (Mikkelsen 1996). The B sensor data obtained with the biaxial probe are less accurate and more sensitive to curvature of the casing than those of the A sensor because the size of the casing groove controls the B-axis sensor alignment (Green and Mikkelsen 1988). The wheels of the probe are designed narrower than the grooves in the casing so the wheels have some freedom to move side to side. Because the A-axis is in line with the wheels, it is not affected by this possible and usual side to side movement of the probe (Richardson 2002). However, the B-axis readings will be affected by the location of the wheels in the A-axis grooves. Thus, for the biaxial inclinometer, it is generally recommended that the A-axis sensor (i.e., parallel to the wheels) be oriented in the principal direction of the landslide so deformation corresponds to a positive change. The direction of the landslide is usually marked Ao and corresponds to the positive change in movement (Cornforth 2005; Mikkelsen 1996).

If the A-axis is perfectly aligned with the direction of landslide movement, the entire shear movement will be measured in the A-axis and no movement will be detected in the B-axis. However, it is difficult to determine and align the A-axis in the exact direction of the landslide, especially if the slide is not a single unit. Thus, the actual magnitude and direction of movement are determined by vector summation of the two components of movement measured in the A- and B-axes. This summation is illustrated in Fig. 4 where the resultant of movement is determined from the magnitude of movement of the A- and B-axes and the orientation of the Ao direction. Figure 4 shows the resultant magnitude of movement is 110 mm and the direction of the resultant is S47°E based on the Ao being oriented S20°E and the shear movement being 50 and 98 mm in the B- and A-axes, respectively. Thus, determining the direction of the Ao direction is important for determining the direction of the resultant movement.

The direction of the A-axis is usually determined using a compass. The potential problem with using a compass is that sometimes, a metal casing is used to case the upper portion of the hole and to protect the inclinometer from vandalism. This metal casing can affect the compass reading. This has lead to two instances where experts did not agree on the direction of landslide movement until the error was corrected. This error can be avoided by placing a straight object, e.g., a board or tape measure, across the casing in line with the A-axis and holding the compass well above the metal casing to measure the orientation of the straight object.

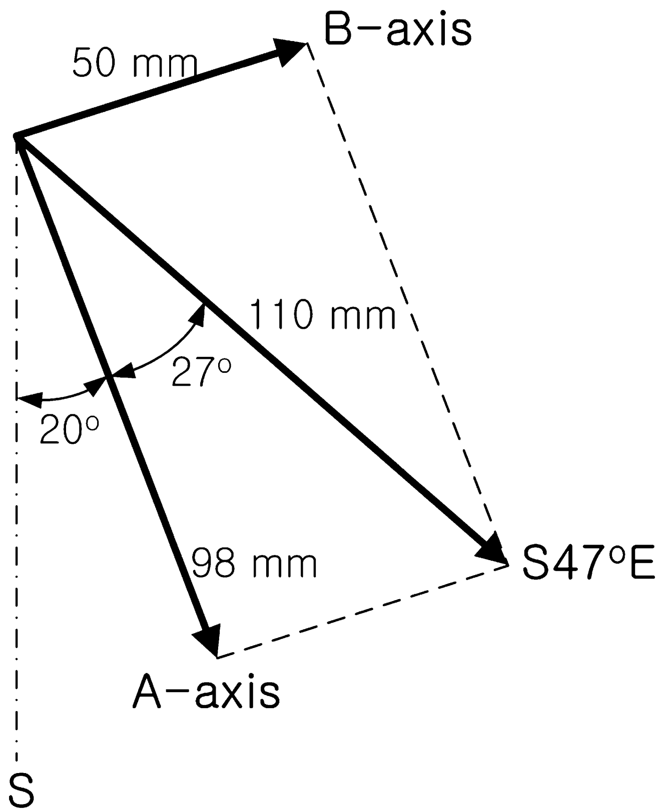

Fig. 4 Determining the resultant magnitude and direction of movement using the A- and B-axes

Proper installation and monitoring of inclinometers

Casing installation

To reduce errors in inclinometer measurements, it is recommended that the inclinometer casing be installed as straight and vertical as possible. Errors in inclinometer measurements are proportional to the product of casing inclination and angular changes in sensor alignment. Therefore, tight specifications on borehole verticality and drilling techniques are preferable (Green and Mikkelsen 1986, 1988). In addition, the bottom of the inclinometer casing should be fixed from translation so the total deformation can be calculated. Thus, the borehole should be advanced to stable ground. This assessment should be based on site-specific factors. A depth of about 6 m or more below the elevation of the expected active zone of movement is suggested. It is convenient to advance one borehole to a greater depth than required for inclinometer measurement and to use the bottom length of the casing for checking the instrument. In addition, readings from this depth can help in detecting and correcting systematic errors (Dunnicliff 1988; Richardson 2002). A case history is presented subsequently that illustrates the confusion that can develop if an inclinometer is not fixed in stable ground.

The inclinometer casing should be flexible enough to move with the soil when the soil deforms laterally. This is especially true if the inclinometer will be used as a warning system to notify nearby residents of increased landslide movement. Frequently, at sites with squeezing ground and/or difficult drilling, a metal casing is used. The inclinometer inside the metal casing will probably be able to detect large horizontal movements, but probably will not be sensitive enough to detect the onset of movement. To facilitate detection of small movements, the inclinometer casing should be made of polyvinyl chloride (PVC) plastic that will readily deform when subjected to movement as is currently used in practice.

The internal diameter of the inclinometer casing usually ranges from 40 to 90 mm (Abramson et al. 2002). Increasing the diameter of the casing will increase the precision of the movement, so the largest casing size should be used where possible. Large diameter casings also allow more shear deformation to occur before the inclinometer probe is not able to pass the distorted segment of the casing. When the diameter of the casing has been reduced to a diameter that does not allow the probe to pass, the inclinometer is referred to as “sheared off” and must be replaced. However, the casing still might accommodate a time-domain reflectometry cable which can remotely sense the onset of movement.

After the borehole is complete, the PVC plastic casing is coupled or glued together in 1.5 to 3.0-m lengths. The casing is lowered into the borehole and oriented so the A-axis is aligned in the direction of movement. The groove in the direction of movement should be marked as A0 to facilitate future movements.

An important aspect of inclinometer installation is the backfill used between the inclinometer casing and the borehole. The annular space between the casing and borehole wall can be backfilled with grout, sand, or pea gravel to ensure that casing movements reflect soil movement and not simply movement of the casing in the borehole. Among the possible backfill materials, grout is the most desirable backfill because grout provides a rigid connection between the soil and casing so movement of the soil is translated directly to the casing. Thus, it reflects an accurate representation of the soil movement. In addition, if sand or pea gravel is used to fill the annular space, voids can develop where the backfill bridges the annular gap. This gap can allow the casing to deform into the void which will produce errors in the inclinometer measurements and/or false indications of movement, as shown in Fig. 5 at a depth of about 12 m. The movement indicated in Fig. 5 at a depth of 12 m is in the opposite direction of the slide movement at a depth of about 31 m. Pea gravel or gravel can also allow the inclinometer to experience greater deformation than grout. In one case experienced by the authors, an inclinometer backfilled with pea gravel recorded a deformation of 88.9 mm, even though the diameter of the inclinometer casing is only 47.6 mm. This can result in confusion because the deformation exceeds the diameter of the casing.

Grout can be delivered either through a tremie pipe inside the casing or through an external tremie pipe outside the casing. Cornforth (2005) recommends the use of an external tremie pipe because this method does not coat any part of the inner grooves of the inclinometer casing with grout. A grout backfill for an inclinometer should consist of a cement–bentonite–water mixture. Initially, cement is mixed with water and then sodium bentonite powder is added slowly. Mixing continues until the slurry reaches the consistency of a thick cream. The sodium bentonite provides plasticity to the grout, which helps to suspend cement particles in a high water–cement ratio mixture, prevents shrinkage during setting, and minimizes bleed (Mikkelsen 2002; Mikkelsen and Green 2003). Of course, the inclinometer should be grouted from the bottom to the top.

When inclinometer backfilling is complete, the top of the inclinometer casing is cut off and protected from traffic and

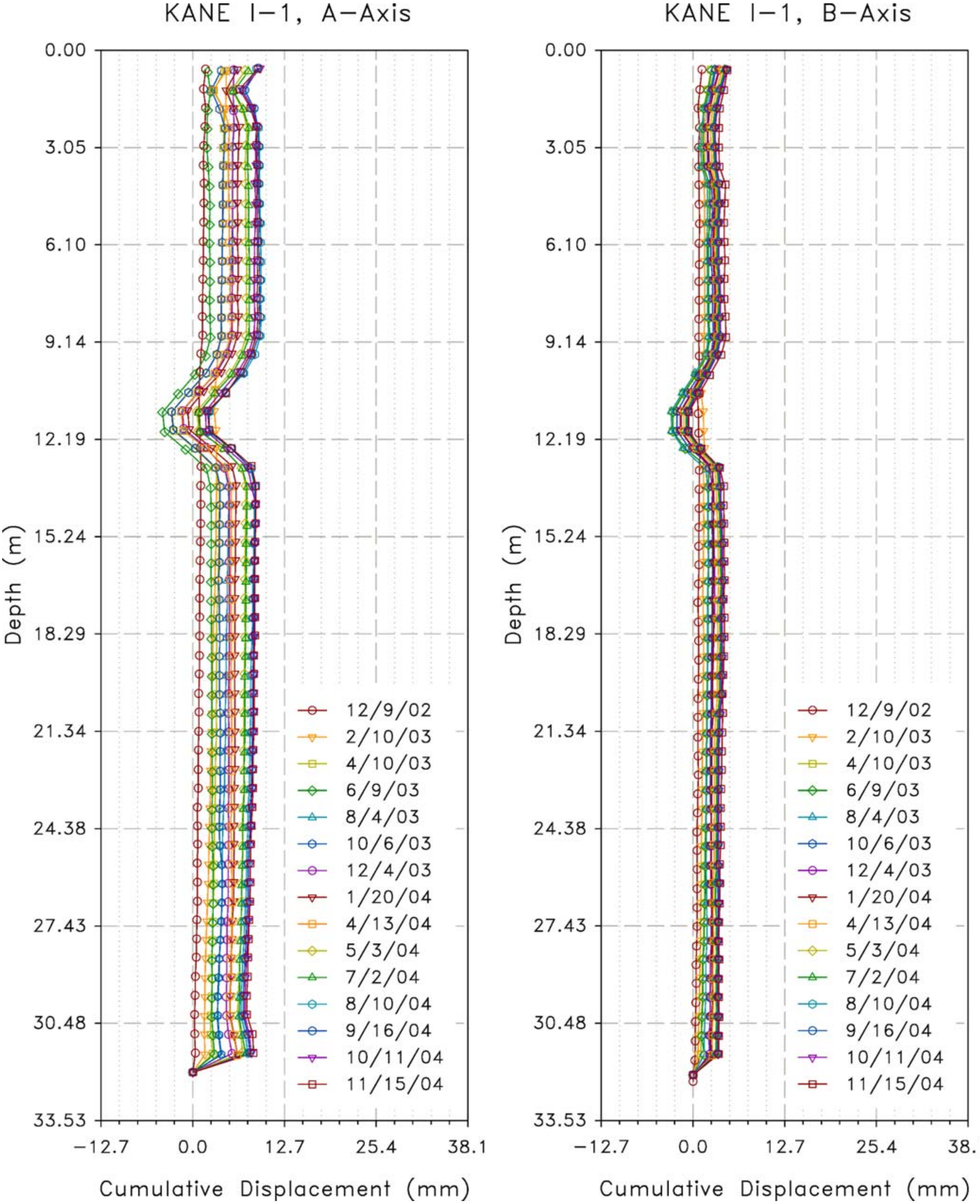

Fig. 5 Example of inclinometer data (I-1 in case no. 3) after readings shown in Fig. 2

vandalism usually with a steel casing. As mentioned previously, the horizontal orientation of the A0 groove should be accurately measured using a compass and marked for identification. It is advisable to wait 1 to 3 days for the grout to set before taking the zero readings (Cornforth 2005). Cornforth (2005) recommends the use of a dummy probe to check that there are no obstructions in the casing after the installation of the inclinometer casing before using the “production” probe to obtain the zero readings.

Inclinometer monitoring

The "zero" readings are important because all subsequent inclinometer readings are referenced to the changes from the zero measurements. The zero or initial measurement of the original profile should be established by at least two sets of readings. If any set of readings deviate from the other, these reading should be rechecked (Cornforth 2005; Mikkelsen 1996).

Using the same inclinometer probe used for the zero reading, the tilt measurements should begin from the stable bottom of the inclinometer. The probe should not hit the bottom of the borehole when it is lowered, so the length of the borehole should be documented and the probe is slowly lowered using the intervals on the cable to the desired depth. Before starting the zero measurements, the probe should be held in the same position for at least 10 min so the probe can adjust to the temperature in the borehole. This procedure prevents errors due to sensor warm-up drift (Cornforth 2005; Richardson 2002).

For the first measurements after the "zero" readings, the probe is lowered to the bottom of the casing with the wheels in the A0 groove. When the probe reaches the bottom of the inclinometer, the cable is clamped in the jaws of the pulley on the foot marker corresponding to the lowest depth reached in the zero readings. The probe should then be raised to the surface in the intended increments with readings of the A0 and B0 directions at each interval. The measurement interval equal to the wheel-base of the probe is commonly used to achieve the maximum precision. The B0 direction is at 90° clockwise from the A0, and the tilt in the B-axis is measured by the second sensor in the probe. After all readings are taken with the wheels in the A0 groove and the probe reaches the surface, the probe is carefully removed and rotated by 180° so that the lower wheels are inserted into the A0 groove and another set of readings is obtained in the A180 and B180 directions. Measuring locations must be identical to those in the first traverse. This second sets of readings should have the opposite tilt of the first set (Cornforth 2005; Dunnicliff 1988; Mikkelsen 1996; Richardson 2002) which provides a check on probe accuracy.

Inclinometer measurements generally are recorded as the algebraic sums or differences of the pair of readings in the two-pass survey. Computing the algebraic difference of the readings for each depth eliminates errors resulting from irregularities in the casing and instrument calibration (Abramson et al. 2002; Mikkelsen 1996). Dunnicliff (1988) recommends checking inclinometer measurements by calculating the algebraic sum of each pair of readings 180° apart and refers to this as the "checksum". Ideally, the checksum should be zero because the two readings have opposite signs. However, in practice, checksums are not zero because of bias in the probe, variations in the grooves, and the positioning of the wheels and/or probe (Slope Indicator 2005). If checksums do not remain constant, errors have occurred and the probe should be recalibrated before subsequent measurements.

Inclinometer accuracy

The precision of inclinometer measurements depends on several factors such as the design of the sensor and quality of the casing, probe, cable, and readout system. It is extremely important that all of the grooves are carefully cleaned and the sensor unit is calibrated regularly. Even if all of these factors are addressed, there still can be errors in the readings. Product literature from Slope Indicator (2005) states that the system field accuracy is empirically ±7.8 mm per 30 m of casing, subject to some qualifiers. This total error is a combination of both random and systematic errors and is important in landslides that have not moved significantly. If the movement measured in a slope inclinometer does not exceed the system field accuracy, the consultant/expert should view this movement with caution and within the expected error of the probe. This will prevent a false conclusion that a landslide exists because the movements are within the expected error and thus may not be slide-related. Therefore, understanding the typical errors that exist in inclinometers is important for consultants/experts to evaluate the presence, character, and causation of a landslide.

Random errors versus systematic errors

Mikkelsen (2003) indicates that a random error is typically no more than ±0.16 mm for a single reading interval and accumulates at a rate equal to the square root of the number of reading intervals over the entire casing. On the other hand, the systematic error is about 0.13 mm per reading under controlled laboratory conditions, and it accumulates arithmetically (Slope Indicator 2005). Thus, systematic errors are more important and significant than random errors and should be avoided.

The systematic errors may mask shear movements occurring at slip surfaces and thus should be evaluated and corrected during data processing. Mikkelsen (2003) provides an explanation of systematic errors and methods to detect and correct systematic errors. The main types of systematic errors are bias-shift error, sensitivity drift, rotation error, and depth positioning error, each of which are summarized in the following subsections. Systematic errors can be minimized by installation of casings that are vertical and free from excessive curvature and by using mathematical correction procedures. However, random errors cannot be corrected but are less influential because they tend to remain constant, whereas the systematic errors tend to vary with each survey (Mikkelsen 2003). Thus, the limit for precision for a 30-m measurement (i.e., 60 reading intervals with a 0.5-m probe) is about ±1.24 mm after all of the systematic errors are removed.

Bias-shift error

The sensor bias is the reading of the probe when it is vertical. Initially, the sensor bias is set close to zero in the factory, but it may change during field use. If the sensor bias is zero, the readings of A0 and A180 should be numerically identical but opposite in sign. Thus, the magnitude of the bias shift can be evaluated using the checksum, which should be zero if there is no bias shift. However, there is usually a slight bias in the output of the probe. This is referred to as a bias shift or zero shift. This bias-shift error is related to a small change in the bias of the inclinometer probe over time. The bias-shift error is the most common systematic error and can be corrected by the standard two-pass reading of both A0 and A180 directions (Mikkelsen 2003). The bias-shift error can be usually eliminated during data reduction, but sometimes introduces errors if there is a change in the bias between opposite traverse readings, i.e., 180° apart, or if the opposite traverse readings are missed. If the error is systematic, the bias is a constant value that can be added to each reading and appears as a linear component in the inclinometer plot (Slope Indicator 2005).

The bias-shift errors may result from slight jarring of the probe due to rough handling by the operator such as dropping or bumping the probe against the pulley assembly and from warm-up drift (i.e., sensor temperature equalization; Mikkelsen 2003; Slope Indicator 2005). The bias-shift error (BSE) caused by a constant bias shift in a 500-mm Digitilt probe (Slope Inclinometer 2005) is expressed by Mikkelsen (2003) as:

$$BSE = (0.01\ \text{mm}) \times b \times N \tag{2}$$

where BSE is the total bias-shift error (mm), b is the bias in units, and N is the number of reading interval. For example, in a 30-m-long inclinometer casing, N would be 60. For a bias-shift (b) of 10 units, the total bias-shift error at the top of the casing is equal to 6 mm. Thus, the readings or displacements at the top of the casing should be reduced by 6 mm, and the readings below the top casing should be proportionally reduced depending on depth.

The bias-shift error can be removed by subtracting the algebraic difference between readings of A0 and A180 (i.e., A0 − A180) at each measurement interval. The correction should be made to the measurements in stable ground where no later displacement is expected. Therefore, it is beneficial to have a significant length of the casing in the stable ground, typically, 1.5 to 3.0 m into stable ground (Mikkelsen 2003). The bias-shift error at a certain data set is eliminated by correcting differences between the initial and subsequent (A0 − A180) readings along with a correction unit that is the difference of the mean bias shifts between the two data sets over the stable ground. The difference between the corrected subsequent data set and the initial data set should be close to zero in the stable ground where no lateral displacement is expected. The corrected data are then converted to lateral displacement using the probe calibration factor (i.e., 0.01 mm/unit).

Sensitivity drift

The causes of sensitivity drift are a drift in the operation amplifier in the pre-amplifier of the probe. The sensitivity drift is directly proportional to the magnitude of the readings, and it varies between data sets but is relatively constant for each data set (Mikkelsen 2003). This is the least common error, but it is often the most difficult error to identify. If the error is recognized, it is easy to correct by having the probe factory calibrated and then applying a suitable correction factor (Mikkelsen 2003).

Rotation error

The rotation error occurs when the inclinometer casing deviates significantly from vertical. If the accelerometer sensing axis in the A-axis is rotated slightly towards the B-axis, the A-axis accelerometer will be sensitive to inclination in the B-axis. The B component in the A-axis reading is the A-axis rotation error, as can be seen in Fig. 6. The rotation error angle (Δ) in Fig. 6 can be expressed as:

$$\Delta = \sin^{-1}\left(\frac{r}{s}\right) \tag{3}$$

The rotation error can be detected by identifying that the casing is severely out of vertical alignment by the shape of the casing deformation and by observing that the lateral displacement graphs in both directions (A- and B-axes) resemble each other (Cornforth 2005). The rotation error correction can be accommodated in the DigiPro or Gtilt software by entering the correction value as sine of the rotation error, Δ, (Mikkelsen 2003). In practice, rotation errors can occur when a replacement or different inclinometer probe is used for measurement at a site. Therefore, it is highly

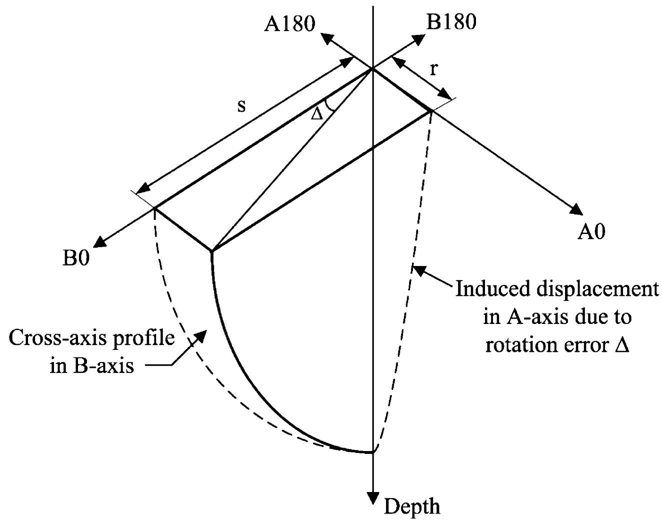

Fig. 6 Schematic illustration of rotation error as a function of cross-axis inclination (from Mikkelsen 2003)

recommended to use the same probe during the entire monitoring program.

Depth positioning error

The depth positioning error results from the probe being positioned at different depths than the "zero" readings in the casing. The difference in the vertical position of the probe is usually caused by a change in the cable reference, cable length, and/or compression or settlement of the casing (Mikkelsen 2003; Slope Indicator 2005). Cornforth (2005) concludes that depth positioning errors are not common in most landslide cases, but it is time-consuming to quantify and correct the depth positioning errors in practice. The top of each casing should be surveyed periodically to determine if a change in elevation has occurred due to slide movement, and the same cable used for the zero readings should be used for subsequent readings.

Slope inclinometer case histories

Case no. 1—Locating the critical failure surface and back analyses

Slope inclinometers are vitally important in determining the critical failure surface. Determining the critical failure surface is important for defining the size of the slide mass, causation, and back calculation of the mobilized shear strength parameters. One of the main uncertainties in the stability analysis is the shear strength of the problematic layer at the time of sliding. This is problematic because of difficulties in obtaining a representative and undisturbed sample of the material, the fact that the sample is probably not representative of the shear strength before sliding, and the ability to simulate the field in laboratory size devices. To overcome this dilemma, a limit-equilibrium back analysis of the landslide is usually conducted to investigate the shear behavior and overall shear strength of the weak layer during the history of the slope. However, a proper back analysis is frequently not performed for many reasons, including the improper use of slope inclinometer data and search for the critical failure surface.

Several other cases could have been used to demonstrate the appropriate use of slope inclinometers in determining the critical failure surface and conducting a back analysis of the landslide than the one presented. However, Fig. 7 presents a cross-section from one case history that involves a single-family residence atop an approximately 70-m-high cutslope for a major east–west state highway. This residence and a prior residence in the essentially same location were distressed by the cutslope. The opposing expert in this case failed to utilize the only slope inclinometer at the cutslope toe when locating and defining the critical failure surface. Instead of considering a deep bedrock landslide through the inclinometer which was "sheared off" at a depth of 10 m at the slope toe, the expert concluded that periodic heave of the highway pavement was caused by expansive soils, differential settlement caused by a transition from natural to fill material, and/or poor pavement construction. This might be a reasonable hypothesis if the inclinometer at the cutslope toe had not been sheared off at a depth of 10 m. The stability analyses performed by this expert for the slides on the face of the cutslope also did not include the slope inclinometer as shown in Fig. 7. Figure 7 also shows that a deep bedrock failure surface can incorporate/explain the heave of the highway pavement, the sheared inclinometer, the distressed residence, the failure surface found in large diameter borings near the residence, and the slope inclinometers installed adjacent to the residence.

All slope inclinometers should be included on the various cross-sections to better understand the location of the critical failure surface. Even inclinometers that do not show any shear movement should be included because the failure surface must be below these inclinometers. The depth of shear movement in inclinometers that are greater than 15 to 30 m, depending on the geology, should be included on the cross-section but given different symbols depending on the distance from the cross-section. The inclinometers more than 15 to 30 m away should not be given less weight than closer inclinometers when determining the critical failure surface. Using the appropriate slope inclinometers and the location of surface features, possible failure surfaces should be sketched on the cross-section. The failure surface that explains all of the observed movement and distress is probably the critical failure surface.

A back-analysis should be conducted for each cross-section to determine the critical cross-section and the mobilized shear strength parameter, i.e., friction angle (Stark et al. 2005), for the weak layer. The back analysis must use the critical failure surface so the minimum value of friction angle, ϕ, is obtained. A common problem is a search for the critical failure surface instead of forcing the failure surface to pass through the sheared inclinometers and the observed surface features. It is proper to conduct a search for the failure surface that yields the lowest back-calculated friction angle between the inclinometer(s) and the surface features. This can be accomplished by fixing the failure surface in the slope stability software at the location of the inclinometers and the surface features and allowing the software to search between these fixed points.

This process should be repeated for several cross-sections to determine the critical cross-section and the critical failure surface. The critical cross-section is not automatically located at the center of the slide mass. In addition, the critical cross-section should be parallel to the direction of movement determined from the slope inclinometers. The resultant vector of each inclinometer should be plotted on a plan view to determine the direction of sliding and the various cross-sections that should be drawn parallel to this direction. It is possible for a landslide not to move as a single unit, and thus, all of the inclinometer direction vectors may not be in the same direction.

In summary, all of the inclinometer data should be used with the surface information to establish as much of the critical failure surface as possible. In the lengths of the failure surface that are not well defined by inclinometer data, a search can be conducted using slope stability software to locate the critical failure surface between the inclinometer and surface data. This should be repeated for a variety of cross-sections parallel to the direction of movement determined from slope inclinometer data to locate the critical cross-section and determine the mobilized shear strength.

Case no. 2—Determining the magnitude and direction of movement

In this case, the opposing experts reported different directions or orientations for the direction of movement measured in a number of slope inclinometers. Coincidently, the different directions supported the different causation hypotheses that were being advanced by the two experts. One example of the difference in the calculated vectors for this case is one expert reported the direction of movement as S47°E, while the first author reported the direction

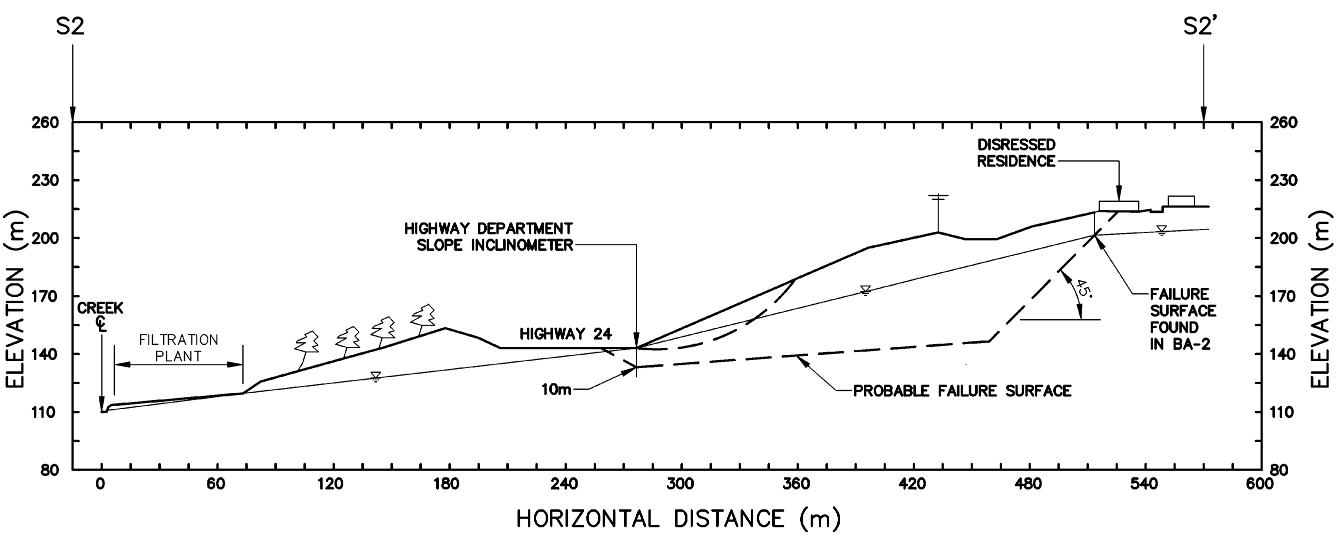

Fig. 7 Use of slope inclinometer data and searching for the critical failure surface

of the inclinometer as S37°W. The vectors developed by the opposing expert pointed to the location of maximum grading, 6.7 m, which the expert believed caused the slide by removing toe support. The vectors calculated by the first author pointed to a location with only 1.8 to 2.4 m of grading and thus concluded that this surficial grading did not trigger the large and deep (about 37 m) landslide. After considerable debate, it was determined that the difference in the vectors was caused by an error in measuring the direction of the A0 axis because of the presence of a metal casing as described previously.

Case no. 3—Importance of inclinometer depth

In this case, the locations of slope inclinometer I-1 and I-2 are indicated in Fig. 8. Slope inclinometer I-2 is located on a slope adjacent to a housing development, and the resulting data are shown in Fig. 9. The top of the inclinometer is located at an elevation of about 124 m above mean sea level. Below a depth of 26.2 to 26.5 m (see Fig. 9), no significant movement of the casing was measured. At a depth of 26.2 to 26.5 m, there is a distinct offset in the inclinometer casing, indicating shear movement of about 50.8 mm as of 3 July 2003. More importantly, above this depth, the inclinometer casing is essentially vertical, indicating a rigid block is moving on a distinct shear surface. The shear movement of 50.8 mm is significant and well outside the possible range of the accuracy errors discussed above. In fact, this inclinometer may become unreadable if additional displacement occurs because the diameter of the casing is only 73 mm and additional shear displacement may prevent the probe from passing a depth of 26.2 to 26.5 m. The vector of movement for the readings is roughly perpendicular to the slope contours, which indicates that the rigid block is moving away from the top of slope.

Another inclinometer (I-1) is installed upslope of inclinometer I-2 and is shown in Fig. 2. The top of inclinometer I-1 is located at an elevation of about 133 m above mean sea level or at an elevation that is about 10m higher than the top of inclinometer I-2. I-1 is also located about 180 lineal meters upslope of inclinometer I-2. The movement in I-1 is shown in Fig. 2 and corresponds to a similar elevation, not depth, as observed in I-2 but with a significantly smaller magnitude (about 15.2 mm instead of 50.8 mm as of 3 July 2003). I-1 is upslope of I-2 by ten vertical meters, but the length of the inclinometer is only 3 m longer. This case history illustrates the importance of installing inclinometers a sufficient depth into stable ground, otherwise confusion about the results can develop. For comparison purposes, I-1 should have extended to a depth of about 40 m so the bottom of the inclinometer would be located at the same elevation (not depth) as I-2.

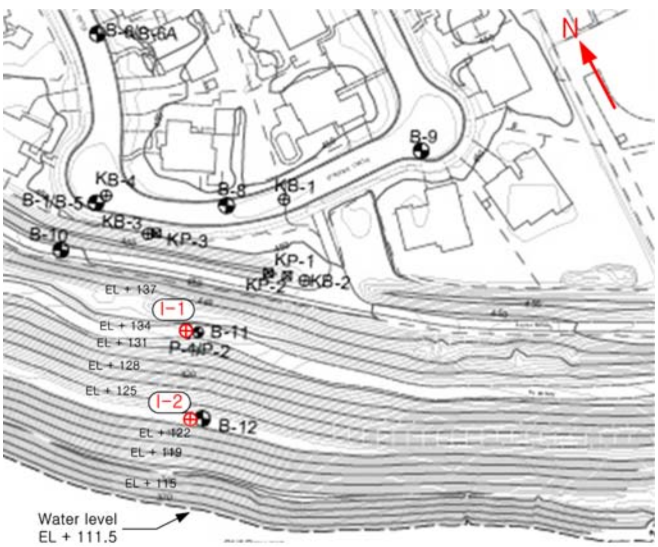

Fig. 8 Location map of slope inclinometers I-1 and I-2

The difference in the magnitude of movement between these two inclinometers caused substantial confusion amongst the four consultants that considered the data. From the data, it is unclear whether (1) a slide block extends from the slope toe and terminates before I-1, which would explain the smaller magnitude of movement measured in I-1 than I-2, (2) the slide block extends behind I-1, which explains the distress observed in the residences at the top of slope, but is not in agreement with the magnitude of movement in I-1, or (3) there is a second slide block involving I-1 that has moved a smaller amount than the slide block that contains I-2.

The first hint of a problem with the data in I-1 is the fact that there is no portion of the inclinometer that has not moved. Thus, the total magnitude of movement at I-1 is not known, even though the various consultants thought 15.2 mm corresponds to the total magnitude of movement. An expert should carefully compare inclinometers to check for accuracy issues and installation errors that render the data suspect. Comparing Figs. 2 and 9 shows that below a depth of 26.2 to 26.5 m in I-2, the shape of the casing is essentially identical to when it was installed. Thus, the 50.8 mm of movement recorded in I-2 is the total amount of movement that has occurred at the location of I-2. Conversely, one cannot determine the maximum amount of movement at I-1 because there is no portion of the casing below the failure surface that has not moved, as clearly shown in I-2. Thus, the maximum amount of movement of the I-1 casing is at least 15.2 mm and could be similar to I-2, i.e., 50.8 mm. To reconcile this dilemma, a comparison of the data in Figs. 2 and 9 shows that the signatures of these two inclinometers are similar, which suggests that a translational movement is occurring at the same elevation in inclinometers I-1 and I-2.

Evidence that the movement in I-1 is probably greater than that shown in Fig. 2 is that not only do both inclinometers show a similar pattern of shear displacement but they also show similar rates of movement. Figure 3 shows the displacement versus time data from I-1 and I-2. The relationships show that the rate of movement in both inclinometers accelerated from April 2002 to November 2002. After November 2002, the movement in both inclinometers slowed but is still occurring. This reduction in displacement rate is caused by implementation of a remedial measure. Thus, the idea of two different slide blocks is not supported after careful comparison of the behavior of I-1 and I-2.

In summary, the similarity in the signature and rates of movement between I-1 and I-2 and the fact of I-1 is too shallow to determine the total amount of movement resulted in the conclusion that the translational slide block extended upslope of I-1. This conclusion is also in agreement with the observed distress in the housing development behind the slope crest. This depth of sliding also corresponds to a slicken-sided clay layer that extends under the housing development. Based on this case history, it is recommended that all slope inclinometers be installed to an elevation (depth) that will ensure that the bottom of the inclinometer will not move and thus provide a fixed reference

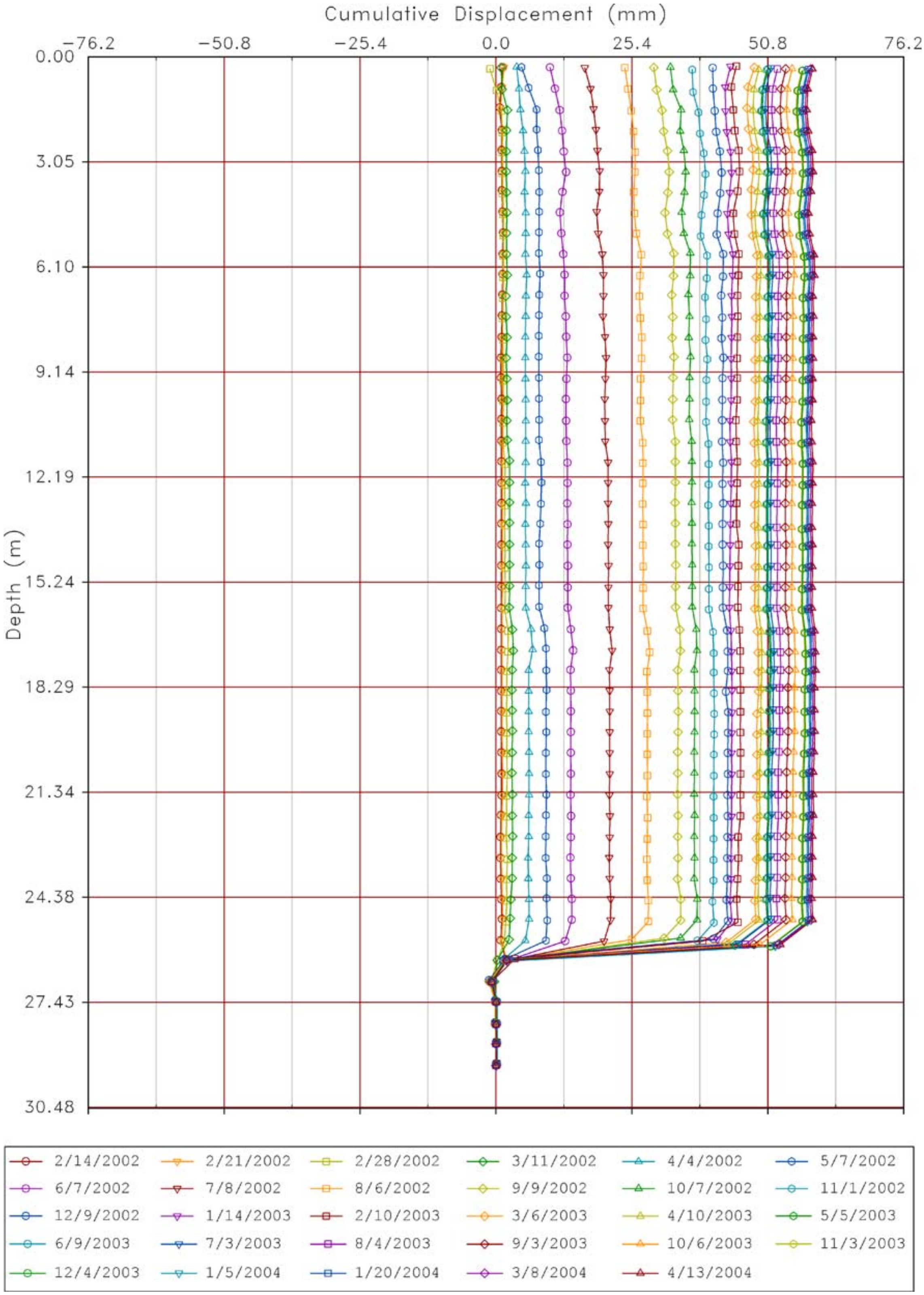

Fig. 9 Results from slope inclinometer I-2 that is downslope of the inclinometer in Fig. 2

for determining the total amount of movement. This can be accomplished by installing adjacent, if not all, inclinometers to the same elevation, not depth. This can be accomplished by increasing the length of the inclinometers, as the borings are located further upslope.

Conclusions

Slope inclinometers are used to determine the vitally important magnitude, rate, direction, depth, and type of landslide movement. This information is used to understand the cause, behavior, and remediation of a landslide. However, many inclinometer measurements fail to achieve these intended aims because of lack of appreciation of the many factors that need to be correctly implemented during installation, monitoring, and data reduction. The installation factors include ensuring the bottom of the inclinometer is located in stable ground, the use of the proper backfill to fix the inclinometer in the slide mass, and the use of a flexible casing so it can detect small amounts of movement. The systematic errors that need to be considered in the data reduction phase include the bias-shift error, sensitivity drift, rotation error, and depth positioning error. This paper presents some guidelines for addressing these installation factors and applying correction factors for common measurement errors. Three case histories are presented to illustrate the confusion that can develop if these installation and monitoring factors are not considered.

Acknowledgment

The contents and views in this paper are the authors' and do not necessarily reflect those of any of the developers, homeowners, consultants, or anyone else involved in the case histories.

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