5. Evaluation of inclinometer measurements

5.1 Introduction

With reference to typical behaviour of Swedish clay soils and the magnitude of changes in key parameter values that can be expected for a slope with unsatisfactory stability conditions, measurements of horizontal movements have been chosen as the most reliable monitoring method for this study. As has been mentioned in previous chapters, a major drawback with such measurements, at least for Swedish conditions, is the rather limited magnitude in movements being developed prior to slope failure. However, a critical evaluation of all possible parameters to be measured, shows that horizontal movements still seem to be the most suitable parameter, as movements will be detected even if the measurement devices have not been installed exactly within the limited zone in the soil where movements actually are being developed. Pore pressure measurement devices, on the other hand, need to be installed exactly within this limited zone to enable detection of changes due to, e.g. movements. The reason for this, of course, is that the hydraulic conductivity of normal Swedish clay soils is too low to allow for a quick dissipation of increased pore pressures in limited zones of a soil profile. It will, therefore, take some time until areas also around the zone where movements actually are taking place will tend to show increased pore pressure values.

Horizontal movements in soil profiles are most commonly detected and measured by means of inclinometers. Whereas there are several different kinds of inclinometers available on the market, they can all, on the basis of the way they are operated, in principle, be divided into two main types, namely the *manual* inclinometer and the *automatic* inclinometer. The basic function of the two types, which will be described more in detail in the following chapters, is the same, as are the basic components. They consist of

- inclinometer tubes (usually made from plastics) which are installed in the soil – for Swedish systems, PVC tubes with a diameter of 55 mm and a thickness of 5 mm are commonly used
- inclinometers
- equipment measuring the inclination of the inclinometer.

It is anticipated that the inclinometer tube is flexible enough to allow for deformation when horizontal movements develop within the soil profile and that the inclinometer can measure the magnitude of these changes. It is furthermore assumed that the inclinometer tube is always installed down to “firm bottom”, or at least to a depth below the ground surface where no significant horizontal movements in the soil will develop. In this context, only slopes are considered, which is why traditional (classical) slope stability analyses can indicate depths where no movements would be expected. In other applications it might be more difficult to evaluate this depth if the inclinometer tube is not to be installed in “firm bottom”.

The main difference between the manual and the automatic inclinometer systems is instead to be found in the way they are operated. The manual inclinometer, which consists of only one single probe, requires, as is reflected by its name, operators to manually handle it throughout the whole process of measuring. The same probe is used to measure in all inclinometer tubes and at all measurement levels. Thus, it has to be mounted and de-mounted on each inclinometer tube to be measured, and also manually moved between them. The automatic inclinometer can be said to consist of a series of inclinometer probes "permanently" installed in each inclinometer tube. Permanently does not in this sense refer to "forever", but rather to the time period, which might be limited or not, during which measurements are to be carried out. Contrary to the manual system, the automatic inclinometers, once they have been installed in the inclinometer tubes, are left there until the monitoring activity is finished. Operators are obviously needed to construct the system of inclinometer probes, as well as to install them at the actual site. At installation, all inclinometer probes are connected to a computerised data collection system, and from that point on, the monitoring operation is more or less "automatic". Of course the data collection system requires supervision, but the inclinometers themselves do not need specific operation, unless they are malfunctioning. It might, however, be somewhat misleading to talk about manual and automatic inclinometers. A more correct terminology would be "mobile" and "stationary", respectively, or "single" and "multiple" inclinometer, which more accurately defines the two different kinds. Nevertheless, the systems are normally referred to as manual and automatic and this terminology will also be used throughout this Thesis.

One advantage of the automatic system compared to the manual is that once installed, it offers the possibility to continuously measure horizontal movements and monitor, e.g. slope behaviour. The only limitation is the sampling frequency of the equipment registering measurement values, but with computers and software of today, data from the individual inclinometer probes can be collected at a frequency well above what would be necessary to fulfill all monitoring operations.

The manual inclinometer gives one set of data each time measurements are carried out, and can in a way be compared with point-wise observations. As manual operation is necessary throughout the process of measuring, it is comparatively expensive. Therefore, data is typically collected only on a few occasions within a typical monitoring project, all of course depending on the slope condition and the length of the monitoring operation.

Furthermore, the calibration process of the two types of inclinometer probes is carried out in different ways, something which gives the manual system one important advantage compared to the automatic system. Measurements with the manual system are absolute, i.e. the exact shape of the inclinometer tube is determined, whereas measurements with the automatic system are relative, i.e. only differences in the shape of the inclinometer tube compared to an initial measurement (zero reading) are detected.

Despite these differences, when it comes to measurements of horizontal movements that are developed in the soil, the two types of inclinometers should give similar results when applied on the same location.

5.2 Description of inclinometer systems

A detailed description of the manual and the automatic inclinometer systems has been compiled by **Tremblay et al. (1997)** along with guidelines for operation. This description was aimed at being somewhat state-of-the-art for an evaluation project of inclinometer measurements which was initiated at the Swedish Geotechnical Institute, partly as an important part of this Ph.D. project, partly within the continuous development efforts of geotechnical equipment at the Swedish Geotechnical Institute.

5.2.1 The manual system

5.2.1.1 Brief background

The Swedish Geotechnical Institute (SGI) has been involved in measuring horizontal movements with inclinometers in soil since the early 1950's. About ten years later, at the beginning of the 1960's, SGI got involved in development of equipment, leading to the manual inclinometer system still in use today. **Kallstenius and Bergau (1961)** give a comprehensive description of the first systems which were developed by SGI. Three different kind of manual inclinometers are described:

- *Stånginklinometern* – "the rod inclinometer", which was only used for measurements in superficial soil layers
- *trådtöjningsinklinometern* – "the strain gauge inclinometer", which was an early version of the manual inclinometer used today
- *kontaktpendelinklinometern* – "contact pendulum inclinometer", which only could be used for repeated measurements after completed initial measurements by means of, e.g. the strain gauge inclinometer. One of the advantages with the contact pendulum inclinometer was the use of a micrometer to register measurement values. Therefore, no special training was necessary in order to handle the equipment, which is crucial for other types of inclinometers.

By now, almost 60 years later, among the manual types of inclinometers only the strain gauge type is used, even though it has been further developed since the early 1960's. Throughout the years, a thorough understanding of the manual method, its possibilities and limitations, power and weakness, has developed among engineers; not only those employed by SGI, but among geotechnical engineers in general. Therefore, the manual system is looked upon as a fairly reliable method of measuring horizontal movements in soils. The method is often used for reference measurements when new methods are evaluated, or for calibration of other methods.

From the mid-1980's, the automatic system was developed and rapidly became the most common type of inclinometer system being used. Multiple inclinometers (for the system used at SGI, a maximum of 15 inclinometers) were installed at different levels in the same inclinometer tube and provided longer continuous series of measurement data, which, in some way, became a revolutionary development.

5.2.1.2 Construction

The principal construction of the inclinometer itself is rather simple. It consists of a plate spring, fixed in the upper end and with a weight mounted in the lower end; all contained within a protecting cylindrical cover. An ordinary strain gauge is attached to the plate spring. When the inclinometer probe is inserted into the inclinometer tube, its inclination will vary with the changes of the shape of the tube itself. The plate spring will, therefore, deviate from its normal vertical position, giving rise to a momentum in the spring. The strain gauge will detect this momentum and through the calibration scheme of the inclinometer probe, it can be transformed into a value of the deviation of the plate spring from the vertical, i.e. the inclination of the probe. Comparatively large inclinations, in the range of 80-100 mm/m, can be measured with the strain gauge inclinometer. In order to reduce the pendulous motion of the plate spring, the inclinometer probe is usually filled with silicon oil.

The cylindrical cover is equipped with two steering knobs and one external plate spring, **Figure 5.1**. The spring and the knobs have a dual function. First, they will ensure full contact between the inclinometer probe and the tube throughout the entire measurement operation. Second, they will ensure that the probe all the time is kept at the same distance from the inclinometer tube.

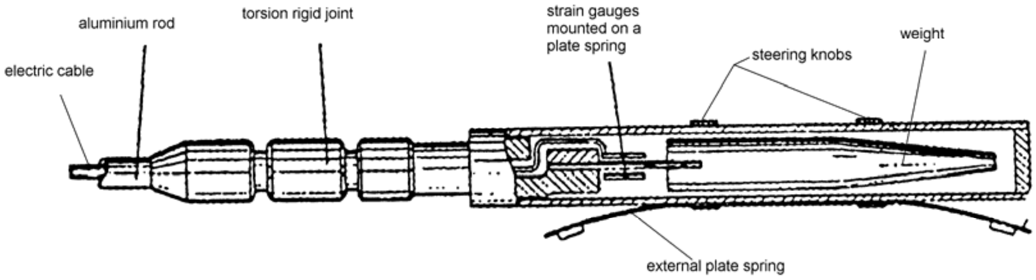

Figure 5.1 Principal construction of the manual inclinometer.

Torsion rigid aluminium rods are consecutively attached to the inclinometer probe to enable lowering down the inclinometer tube to the actual levels where measurements are to be carried out. The individual rods, which are typically of one metre in length (even if shorter variants do exist, such as, e.g. 0.25 m and 0.5 m) must, in order to eliminate errors due to differences in the inclinometer system itself, be combined in the same way each time measurements are carried out. Therefore, all rods are sequentially numbered. Measurements are carried out at levels according to the length of the rods, i.e. usually every metre or every second metre etc. With shorter rod lengths, measurements can be carried out, e.g. every half-metre.

If necessary, rods may be jointed by means of specially developed aluminium sleeves. These provide a torsion-stiff, but not moment-stiff connection, as they allow for free bending movements in one direction.

A calibration scheme is used which, in addition to measurements of relative differences in inclination between different points of time, also enables the measurement of the absolute inclination of the inclinometer probe. Therefore, it is possible to determine the exact shape of the inclinometer tube, which is not possible with other inclinometer systems.

5.2.1.3 Operation

After completed installation of the inclinometer tube in the soil, its total free length is controlled by means of a simple sounding, whereby the levels for the inclinometer measurements also are determined.

The first time measurements are carried out, the measurement directions are determined. Measurements are carried out pair-wise (orthogonal) in two perpendicular directions, usually denoted *X* and *Y*. The main direction is usually the direction of the largest expected horizontal movements, i.e. down slope. The second direction will, thus, be parallel to the slope, **Figure 5.2**.

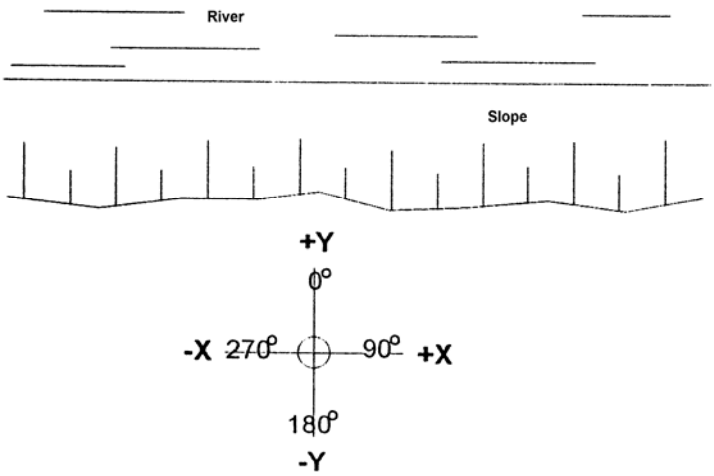

Figure 5.2 Measurement directions for the manual inclinometer system.

In order to guarantee that measurements are carried out in the same directions each time, a special direction device is used. It consists of a graduated arc (0-360°) mounted on top of the inclinometer tube. A rotational arm, equipped with a field glass, is attached to the uppermost rod to enable reading of the graduated arc. The field glass is used to aim at several specific objects (usually one main object and several sub-objects) in the distance in order to fix the position of the graduated arc in the same way each time measurements are carried out. The arc is adjusted so that the reading 0° coincides with the main direction of measurement, e.g. usually down slope. The direction in degrees to the different objects used for aiming is noted, which makes it possible to position the equipment, in principal exactly in the same way each time.

After the graduated arc has been fixed in the exact position, measurements can begin. They are carried out from the bottom of the inclinometer tube and upwards. The entire package of rods with the inclinometer probe is rotated in the inclinometer tube until the rotating arm indicates that the probe is set in the correct position. Measurement values in directions 0° and 180°, and 90° and 270°, respectively, are noted manually or, alternatively, in a data logger. After completed measurements and quality controls at one measurement level, the rotating arm is de-mounted, the rod package lifted and an appropriate amount of rods to lift the inclinometer probe to the subsequent measurement level are de-mounted. The rotating arm is then again mounted on the uppermost rod, and the measurement procedure is repeated.

5.2.1.4 Calculation of horizontal movement

The measurement values from the strain gauge (in micro-strains) can, via calibration constants, be translated to a value of the inclination of the inclinometer probe. The procedure allows for corrections of incorrect positioning of the equipment in the horizontal plane and for deviations of the calibration parameters.

The calculation of the horizontal movements, i.e. the deflections of the inclinometer tube, is practically carried out by means of a computer program. The model implemented in the software used at SGI is based on the integration method between two adjacent points (Simpson’s formula). It is assumed that there is no deflection at a level of 0.5 m below the lowest measurement level. Deflections at other measurement levels are then calculated as (cf. **Figure 5.3**):

$$U_1 = 0.5 \cdot L_1 \tag{5.1a}$$

$$U_2 = U_1 + (5 \cdot L_1 + 8 \cdot L_2 - L_3)/12 \tag{5.1b}$$

$$U_3 = U_2 + (-L_1 + 13 \cdot L_2 + 13 \cdot L_3 - L_4)/24 \tag{5.1c}$$

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$$U_n = U_{n-1} + (-L_{n-2} + 13 \cdot L_{n-1} + 13 \cdot L_n - L_{n+1})/24 \qquad (5.1d)$$

$$U_s = U_{s-1} + (5 \cdot L_{s-2} + 8 \cdot L_{s-1} - L_s)/12 \qquad (5.1e)$$

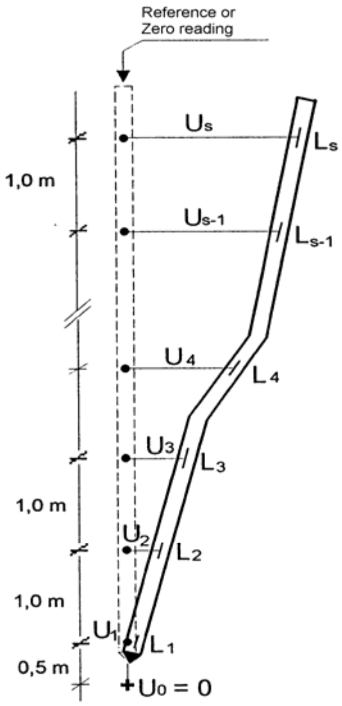


Figure 5.3 Calculation of the deflection of the inclinometer tube for the manual system.

The deflection values (U) are determined with the same set of equations both for the Y- (main direction) and for the X-direction (perpendicular to the main direction), why indexes x and y, respectively, could be born in mind. It should be noted, however, that the above expressions require the distance between adjacent measurement levels to be 1 m constantly. Therefore, measurements carried out by the SGI are always at intervals of 1 m.

The L-values in equation (5.1) are determined as

$$L_X = RES_{korr} \cdot \cos(\theta_{korr}) \qquad (5.2a)$$
$$L_Y = RES_{korr} \cdot \sin(\theta_{korr}) \qquad (5.2b)$$

in which

$$RES_{korr} = RES \cdot KAL \qquad (5.3)$$

$$\theta_{korr} = \theta + \Delta\theta \qquad (5.4)$$

KAL is a number reflecting the noticed deviation of the calibration parameters. A value *KAL* = 1.0 implies no deviations.

Furthermore,

$$RES = (\tan^2(\alpha_X) + \tan^2(\alpha_Y))^{1/2} \quad (5.5)$$

$$\theta = \arctan((\tan^2(\alpha_X)/\tan(\alpha_Y))^{1/2} \quad (5.6)$$

And finally,

$$\sin(\alpha_X) = A_0 + A_1 \cdot X + A_2 \cdot X^2 \quad (5.7a)$$
$$\sin(\alpha_Y) = A_0 + A_1 \cdot Y + A_2 \cdot Y^2 \quad (5.7b)$$

in which

$$X = X^+ - X^- \quad (5.8a)$$
$$Y = Y^+ - Y^- \quad (5.8b)$$

Measurement directions are shown in Figure 5.2.

5.2.2 The automatic system

5.2.2.1 Brief background

When the development of complete monitoring systems, e.g. for slopes, began in the early 1980's, a need for continuous measurements of horizontal movements was identified. The development at the SGI led to the "automatic inclinometer system" still being in use, even though there have been some modifications compared to the original design. The monitoring system was first tested at the SGI test field outside of Norrköping where a man-made research slope was heavily instrumented and driven to complete failure (**Möller and Åhnberg, 1992**).

Today, the "automatic system" is the most commonly used system for measurements of horizontal movements in soil, and the system is still undergoing constant development (see e.g. **Joelsson, 2002**).

5.2.2.2 Construction

The principal construction of the automatic inclinometer probe and the manual inclinometer probe is more or less the same. It contains some kind of device to detect differences in the inclination of the probe when it is inserted along an inclinometer tube.

The cylindrical inclinometer probe contains a pendulum with a magnet mounted above a sensor, which can detect differences/variations in the magnetic field. The pendulum is attached to a plate spring. Inside the probe is also electronic equipment, which transforms the variations in the magnetic field to electric currents.

As for the manual probe, also the protective cover of the automatic probe is equipped with two steering knobs and one external plate spring; firstly to ensure full contact between the probe and the inclinometer tube, secondly to always keep the probe centrally positioned in the inclinometer tube.

The individual probes are connected with plastic rods (distance rods) to create an inner system which can be inserted into the inclinometer tube, usually referred to as the outer system when it comes to automatic inclinometer measurements. The distance rods have a dual function. They should, first of all, keep the probes at the actual measurement levels, but they are also aimed at preventing the inclinometers from rotating, especially during installation. The lowermost distance rod is equipped with a rubber footing in order to ensure good contact against the bottom of the inclinometer tube and also to prevent the inner system from moving. The rods are fabricated from glass fibre plastics and are cut in appropriate lengths. The system, as such, thus, is substantially more flexible than the manual systems, as inclinometer probes practically can be placed at any arbitrarily chosen depth below the ground surface. The distance rods were originally attached by means of a slit and a tube clamp around a dowel at each end of the inclinometer probe. An evaluation project carried out at the SGI during the years 1997 to 2001 proposed that the plastic distance rods instead be attached to the dowel on the inclinometer probe with screws in pre-drilled holes in order to increase the rigidity of the inner system. Today, this adjusted method is used while the measurements analysed within this Thesis were all carried out with the old method, i.e. with tube clamps. The evaluation project with results will be further described in the following sections of this chapter.

A cable is running from each probe through the inclinometer tube up to the surface in order to collect measurement data. In the system currently in use at SGI, a maximum of 15 inclinometer probes can be used in one and the same inclinometer tube. The limitation is set by the available space for cables in the tube. From a practical point of view this often implies that measurements with automatic systems will be carried out at fewer levels than would be the case for the manual system in the same inclinometer tube. The cables from the probes are connected to a sampling unit, which continuously register and record measurement values.

A calibration scheme has determined factors (coefficients) for the transformation of the value of the electric current being measured by the inclinometer to a corresponding value of the actual inclination of the probe. Opposite to the manual inclinometer system, however, the calibration scheme for the automatic system does not allow for determination of the absolute inclination of the inclinometer probe. Measurements can only indicate differences in inclination with reference to an initial arbitrary zero reading.

As the automatic probe is permanently, or at least for a comparatively longer period of time, mounted in the inclinometer tube it can only measure deflections in one direction. The inner system, i.e. the inclinometer probes, cables, and distance rods, are, therefore, installed so as to measure in the direction for which the largest horizontal movements can be anticipated. The correct direction must be kept throughout the complete installation process, as there is no possibility for control of the actual direction of the inclinometer probes afterwards. If measurements are to be carried out in two or more directions, which, of course, can be of interest in certain cases, one complete inclinometer tube with inclinometer probes must be installed in the soil for each direction.

5.2.2.3 Operation

A substantial part of the assembly of the inner system is carried out in advance before going out to the actual monitoring site, typically in a technical laboratory. Inclinometer probes, all with unique numbering, are chosen, calibrated, and quality checked. Distance rods are cut into appropriate lengths so as to assure that the probes are installed at intended depths below the ground surface. The lowest inclinometer probe should preferably be placed as close as possible to the bottom of the inclinometer tube. It is assumed that horizontal movements in the soil are zero or at least of negligible magnitude at the bottom of the inclinometer tube. Thus, the lowermost probe should thus not really detect any movements.

After the inclinometer tube has been installed at the site, a simple sounding is used to determine its free length. As the automatic system is only capable of measuring relative deformations in the soil, it is nowadays rather common that an initial zero reading is carried out with the manual inclinometer before the inner system of the automatic system is put in place in the inclinometer tube. In addition to gaining information about the exact shape of the inclinometer tube, this zero reading also serves as a basis for repeated measurements with the manual inclinometer after the automatic system has been de-mounted; something which, from time to time, might be of interest. Furthermore, sometimes there is a need for measurements with duplicate systems, especially if the automatic system gives somewhat suspicious measurements. This will be dealt with in the section covering the inclinometer evaluation project. Without an initial zero reading with the manual inclinometer, this would not be possible.

The inner system is assembled from the bottom and upwards on site. At the laboratory, a protocol has been compiled showing the sequence of numbered distance rods and numbered inclinometer probes. When the inner system is assembled it is lowered into the inclinometer tube. After about 4 to 5 metres of the inner system has been inserted in the tube, the friction between the steering knobs and plate springs of the probes, the cables, and the inclinometer tube tends to be so large that the system must be pushed down. Sometimes, in rare cases, the friction is too high to enable manual insertion. The installation must then continue with help from the drill rig.

The measurement interval, i.e. the frequency with which registration and recording of measurement data should be carried out, can be determined from object to object, depending on, e.g. the aim of the monitoring operation. The system in use at SGI allows for a minimum interval between two measurements of 5 minutes. However, most commonly, data are collected every 15 minutes, averaged and stored over one hour. For most monitoring situations, this would be sufficient and practical; the sampling frequency is seldom adjusted from this latter pattern. At the chosen measurement interval, i.e. typically every 15 minutes, measurements are collected from each channel, i.e. each probe, a number of times, typically 10 to 20 times. The set of data is rearranged in increased order whereby the median value is chosen in order to avoid influence of unrealistic peak values. A pre-designed quality check of consecutive median values is usually applied. Once every hour, the average value of the medians is calculated and stored. Several other average values are usually also calculated and stored, such as daily averages and weekly averages. The measurement values, which are registered, processed, and recorded, are electronic signals transformed, via calibration factors, to values of the inclination of the inclinometer probe in mm/m.

5.2.2.4 *Calculation of horizontal movements*

The calculation of horizontal movements is made in a rather simple way using the automatic system as, see **Figure 5.4**

$$R = V \cdot L \tag{5.9}$$

where R = the horizontal movement between point i and point $i\text{-}1$
V = measured inclination at point i
L = distance between point i and point $i\text{-}1$.

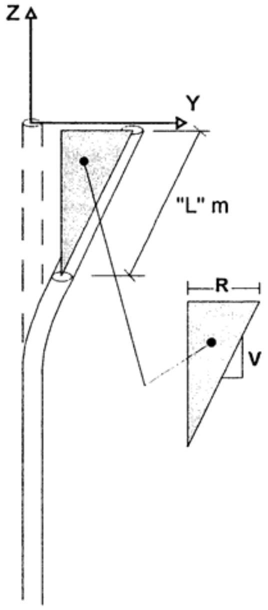


Figure 5.4 Determination of the inclination with the automatic system.

The deflection, i.e. the horizontal movement at a point *i* is calculated as the sum of the movements from the lower end of the inclinometer tube, Figure **5.5**

$$U_i = \Sigma R_i \qquad (5.10)$$

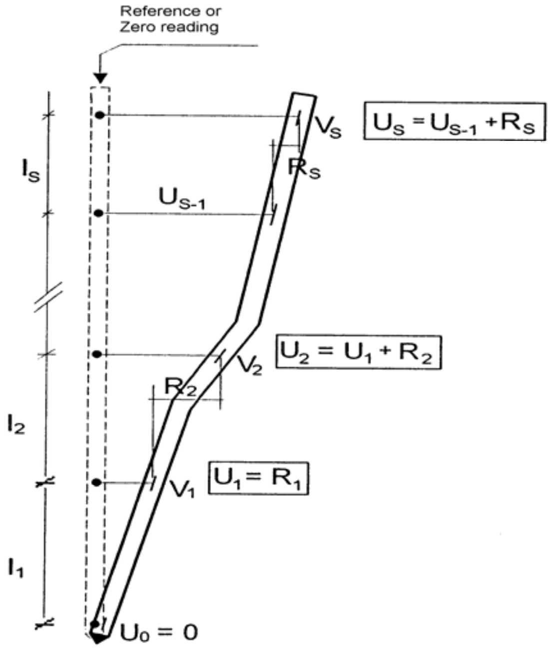


Figure 5.5 Calculation of deflection (horizontal movements) with the automatic system.

5.3 The evaluation project

5.3.1 Background

When the automatic inclinometer system started to be used, a complete new dimension of monitoring opened up. Until then, the manual inclinometer system could provide point-wise observations with certain, usually comparatively long, time intervals in between. The automatic system, on the other hand, did not provide just point-wise observations, but longer continuous series of measurement values.

It was not easy, at first, to realise and evaluate whether the results from automatic measurements were reasonable or not, or in fact correct or not, for that matter. As similar results had never been produced previously, there was, on the other hand, initially no reason to automatically doubt the correctness of the data, which was provided by the automatic system, but, of course, accept them with a certain critical view.

One of the first commercial automatic measurements carried out by SGI was at the so-called Research Slope in Munkedal, Kviström Södra. Measurements were carried out in different sequences for a rather long time period. Inclinometer measurements were carried out at one point about two years before the slope was transformed into a research slope. At this point, which was located in the intermediate zone of the slope, a continuous series of data was, thus, collected for almost four years, while at the two points added later continuous data from a time period of roughly one year and a half exists. One way of presenting the monitoring result is to show the calculated horizontal movement as function of time. In **Figure 5.6**, the result from the original point is presented.

The first observation from Figure 5.6 is that the measurement results after the transformation of the slope into a research slope, in February 1993, seem more even. Another type of inclinometer probes had, by that time, been introduced on the market with more efficient electronics, e.g. when it comes to compensations for temperature effects. The scatter of the measurement data is, therefore, smaller.

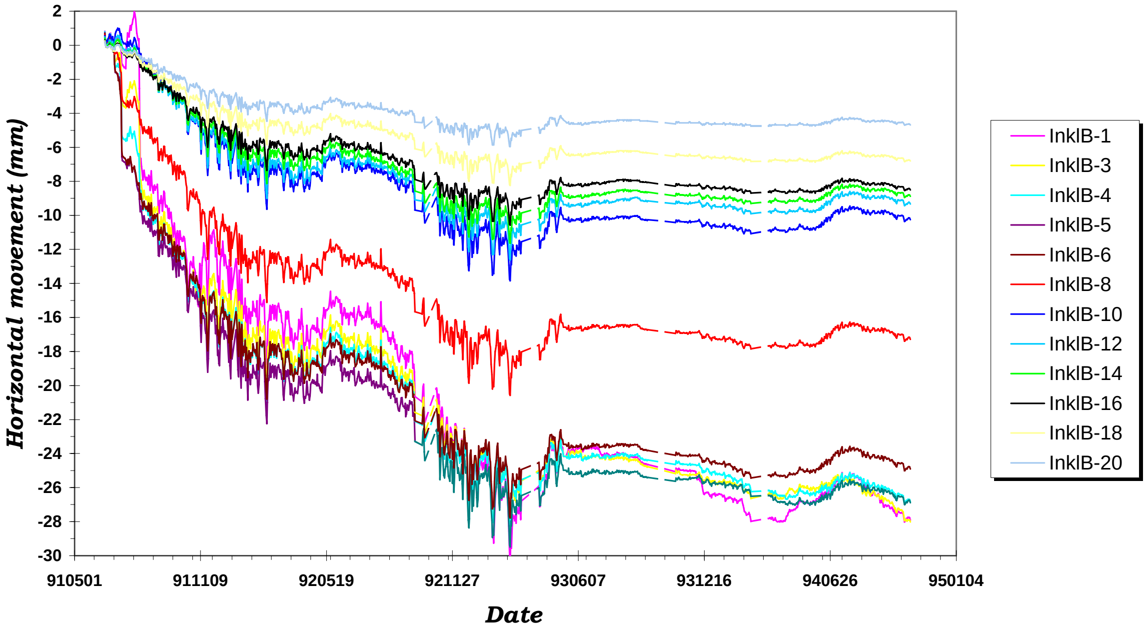


Figure 5.6 Measurement data (horizontal movement vs. time) from Munkedal, Kviström Södra, Point B (intermediate part of the slope). The figures in the legend, e.g. InklB-1, refer to the level of installation for the inclinometer probes. Negative values mean movements down slope.

The second observation, which can be made, is that the rate of horizontal movements, i.e. the increase/decrease of the movements with time, initially seems to be rather high. After roughly a year, in April 1992, the rate of movements tends to even out and then once again accelerate around May the same year. Another retardation in the rate of movements can be observed in the very end of the year 1992. The change in rate of movements in June/July 1994 is due to slope improvements and will be further elaborated on in chapters that follow.

A similar figure can be drawn up for Point A, which is one of the additional measurement points within the research project, **Figure 5.7**, located in the active zone at the slope crest. Therefore, a continuous series of data exist only from the beginning of 1993 and until November 1994 when the automatic system was de-mounted.

The trend for the rates of horizontal movements, which can be observed, is similar to the one at Point B, i.e. an initially high rate, gradually decreasing with time. The lowermost inclinometer probe, at level –46, does not show any movements to occur, something which can be expected, and also a necessity for the calculation of movements from measured differences in inclinations for the other probes.

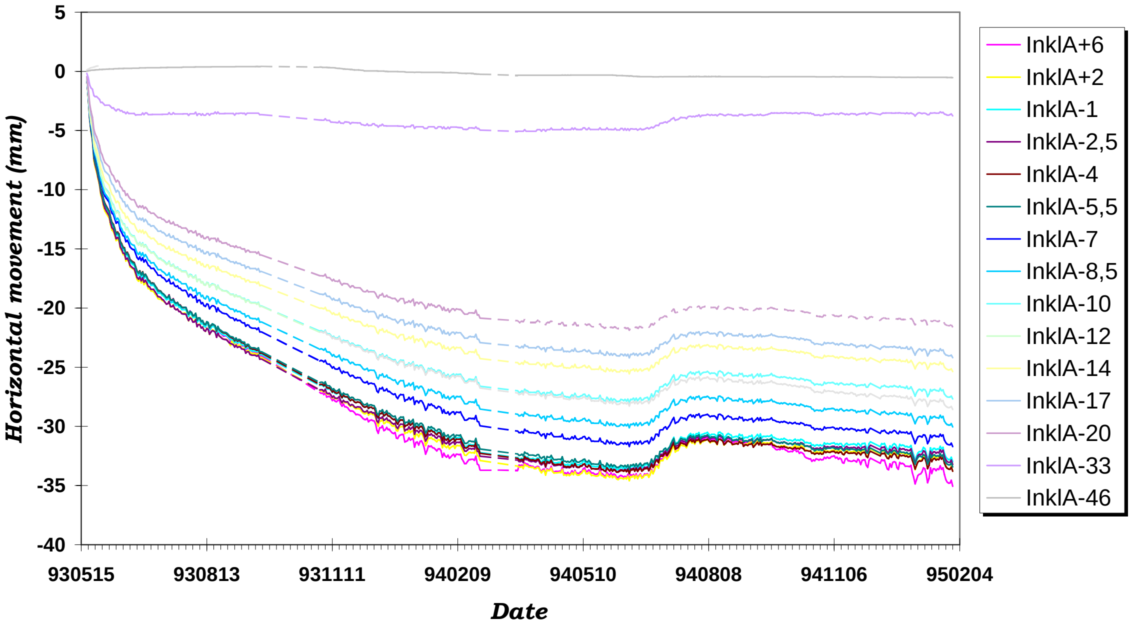


Figure 5.7 Measurement data (horizontal movement vs. time) from Munkedal, Kviström Södra, Point A (active part of the slope). The figures in the legend, e.g. InklA+6, refer to the level of installation for the inclinometer probes. Negative values mean movements down slope.

A certain variation in the rate of horizontal movements over the year can be expected due to seasonal variations, usually called “the natural life of the slope”. There are several reasons for such natural variations, e.g. changes in water content, freezing and thawing processes, changes of water level in adjacent water courses etc.

Some variation in the rate of horizontal movements would, thus, not be too surprising. However, the question came up whether the first period of roughly a year with a high rate of horizontal movements actually is true, and especially the very high rate observed during the first couple of months. A zero reading with the manual inclinometer had been done prior to installation of the automatic system, but a second measurement with the manual inclinometer would require the automatic system first to be de-mounted. No "extra" inclinometer tubes hade neither been installed, which could have been used for quality control of the automatic system, by simultaneously follow up with the manual inclinometer.

By this time, some series of measurements had been collected with the automatic system, and it had in fact gotten some critics. Engineers began to question the accuracy of the measurements. What if the first periods of high rates of deformation are not true? From Figures 5.6 and 5.7, it seems as if "true" measurements are obtained only after a year or more. Taking into consideration that most monitoring projects are considerably shorter than a year in time, engineers at the SGI were concerned with these new findings.

Around the same time, at the beginning of 1992, another long-term slope monitoring project was also in operation using the automatic system, namely at the hospital in Lidköping. A similar presentation of the measurement result as was previously done for the slope in Munkedal, **Figure 5.8**, shows the interesting finding of horizontal movements up-slope (positive values of the inclination), which, of course, are not physically possible to explain or even motivate.

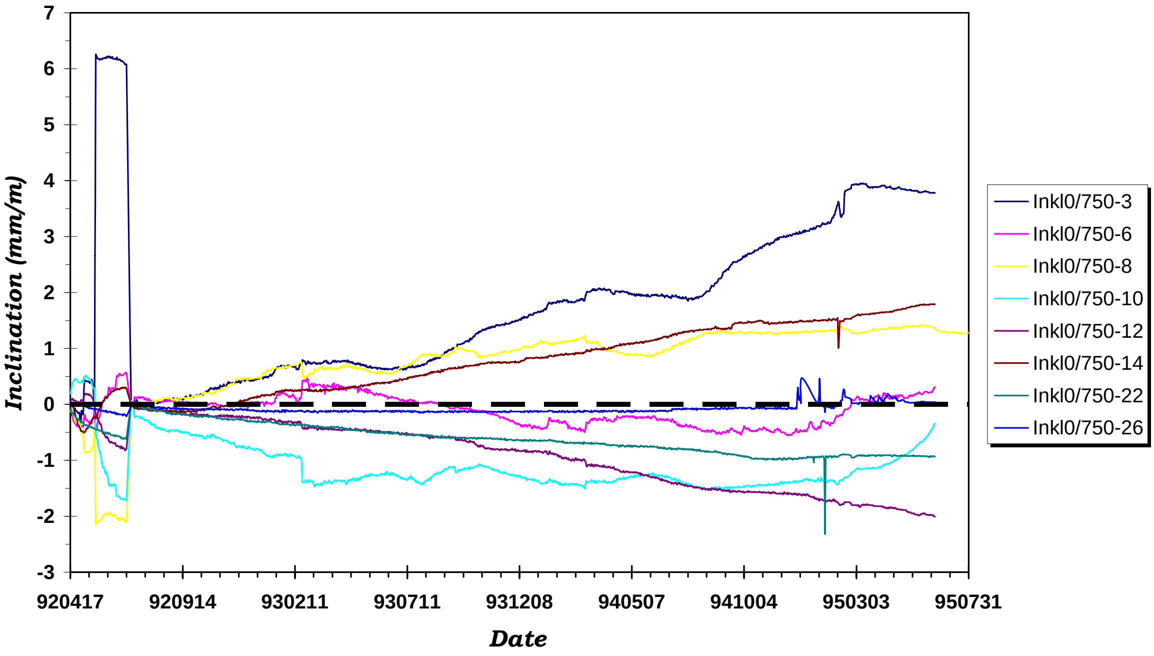


Figure 5.8 Measurement data (inclination vs. time) from Lidköping, Section 0/750. The figures in the legend, e.g. Inkl0/750-3, refer to the level of installation for the inclinometer probes. Negative values mean movements down slope.

When the inner system, i.e. the inclinometer probes with distance rods in between, was de-mounted at Lidköping, special attention was given to controlling the direction of each inclinometer probe when it was removed from the inclinometer tube. The only reason for inclinometers indicating movements in impossible directions was thought to be that they, of some reason, had not been installed correctly. It was somewhat surprisingly concluded that the direction of many probes actually deviated quite a lot from the intended direction of measurement, something which then would support the measurement data presented in **Figure 5.8**.

As inclinometer measurements were chosen as the basis for comparisons between field measurements and results from numerical analyses in this Thesis, a more thorough investigation of the accuracy of inclinometer measurements called for attention. A special Evaluation and Research project was therefore initiated at the Swedish Geotechnical Institute, partly within this Ph.D. work, partly as an evaluation and improvement project for geotechnical equipment.

The Evaluation and Research project paid attention both to the manual system and to the automatic system. The intention was to investigate and evaluate all questions, which had been raised so far, to find answers to them, and try to adjust and improve the systems to meet and fulfill necessary demands for accurate measurements.

The aim of the Evaluation and Research project was to

- critically evaluate all the criticism which had come up and all the experience gained from the use of the systems
- increase the knowledge and performance of the measurement methods as such
- investigate the torsion rigidity of the rod package of the manual inclinometer
- investigate installation effects which might be present with the automatic system
- investigate the stability and the long time performance of the automatic system.

The project was divided into three parts; a) investigations in a horizontal inclinometer tube indoors, b) investigations in a vertical inclinometer tube indoors, and c) investigations in vertical inclinometer tubes installed in rock.

From the beginning, it was thought that the investigations in the horizontal inclinometer tube would be sufficient to conclude if there were deviations from the intended direction of installation of the inclinometer probes and the final direction after completed installation. The idea was to measure the rotation of the probes that might be along the inclinometer tube. For practical reasons, it is considerably more difficult to carry out such vertical tests. First, laboratory space is needed to host vertical inclinometer tubes of more than 10 metres. Second, accessing vertical tubes of such a length will be difficult. However, when following up and continuously evaluating results, it was concluded that only horizontal tests were not representative enough, and that tests also in vertical inclinometer tubes would be necessary. The last investigations, involving inclinometer tubes installed in rock, were carried out to investigate both the repeatability of inclinometer installations,, and the long time stability of the automatic system. Since the inclinometer tubes were installed in rock, no horizontal movements were expected to occur, and the automatic system should not register any movements. Some questions had been raised whether there was a drift of the zero values for the automatic system, resulting in inaccurate measurements.

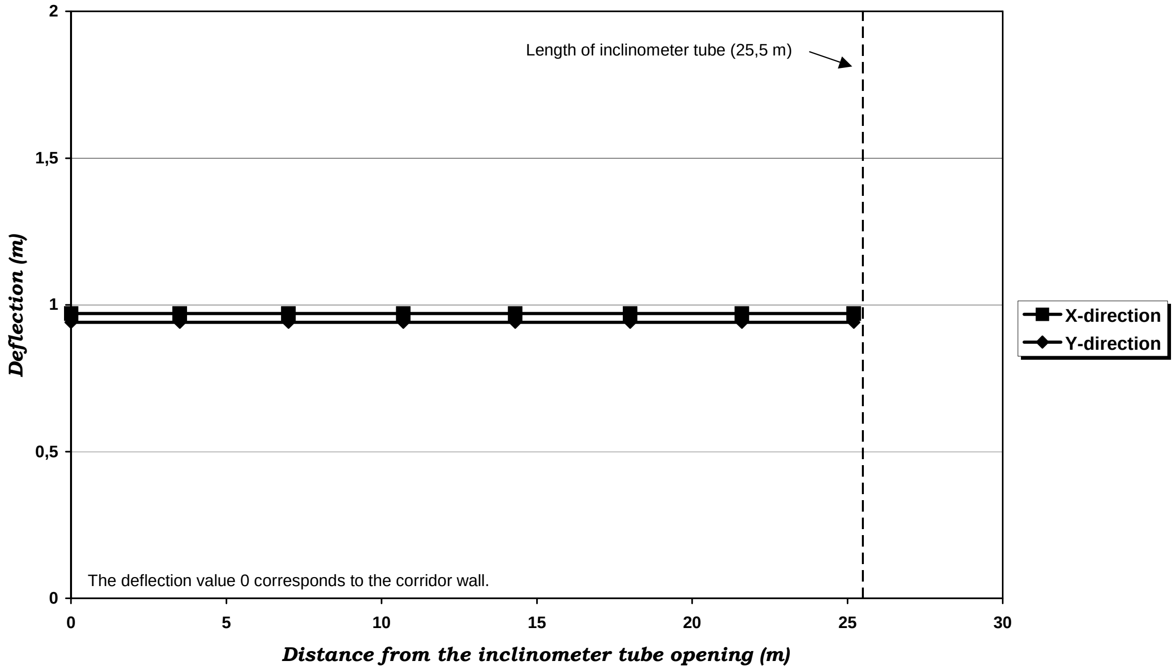
5,3.2 Tests in horizontal inclinometer tubes

All tests with horizontal inclinometer tubes were carried out in a very long corridor in the basement of the SGI building. The main aim with the tests was to clarify whether the direction of the individual inclinometer probes deviated from the intended installation direction. The intended installation direction should in a real situation coincide with the measurement direction, i.e. with the direction in which the largest movements are anticipated. Tests were also carried out to investigate the repeatability of installation.

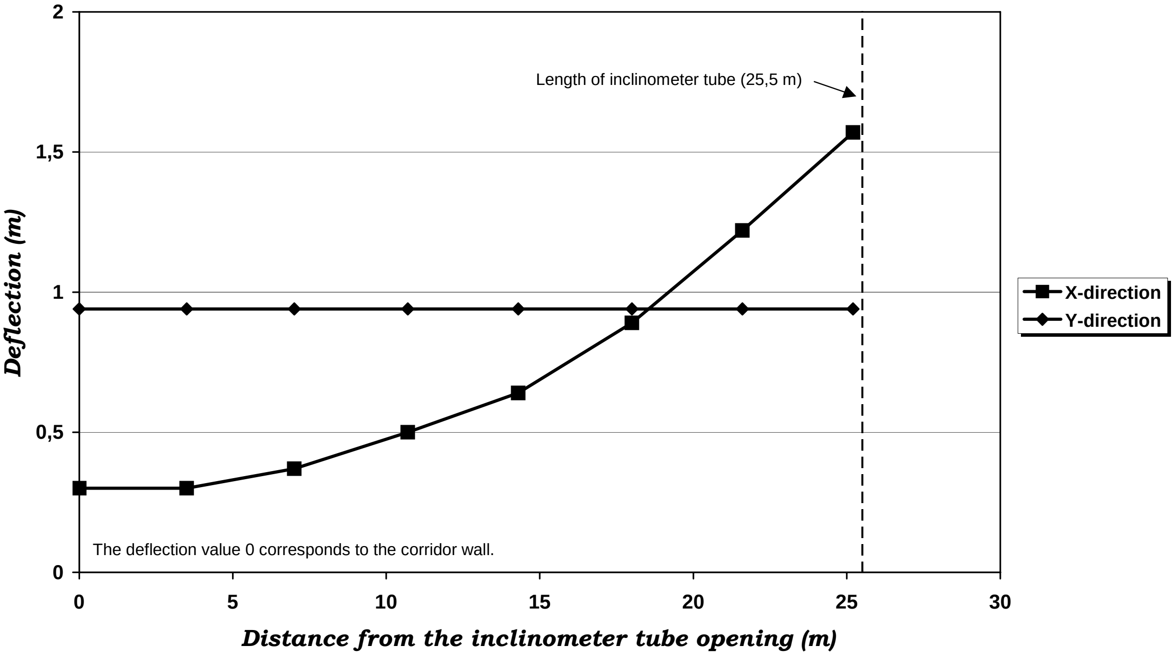
A transparent plastic tube with a length of 25.5 metres and with the same basic properties as a standard inclinometer tube was mounted on specially designed supports in the cellar corridor. Ink lines were drawn along the periphery of the tubes, corresponding to a radial angle of 0° (upwards), 90°, 180° (downwards), and 270°. By this arrangement, the rotation that might be of the inclinometer probes during installation could be detected and quantified by measuring on the tube with reference to the ink lines.

During parts of the tests, the supports were used to deflect the tube in different controlled ways. Measurements with both the manual and the automatic system were then carried out to see if the known shape of the inclinometer tube could be captured. Originally. the test program included four different unique shapes of the inclinometer tube. However, as it was realised that also tests in vertical tubes would be necessary, the horizontal test program was decreased, and only three shapes were actually being analysed, **Figures 5.9**, **5.10**, and **5.11**.

The X- and Y-directions correspond to deflection in the vertical and the horizontal direction, respectively. In the figures, the different directions have been separated from each other, for clarification. The figures should thus be used only for relative measures of the deflection.



1.1.1.1
Figure 5.9 Shape-1 for tests with horizontal inclinometer tube. X- and Y-directions correspond to vertical and horizontal directions, respectively.



1.1.1.2
Figure 5.10 Shape-2 for tests with horizontal inclinometer tube. X- and Y-directions correspond to vertical and horizontal, respectively.

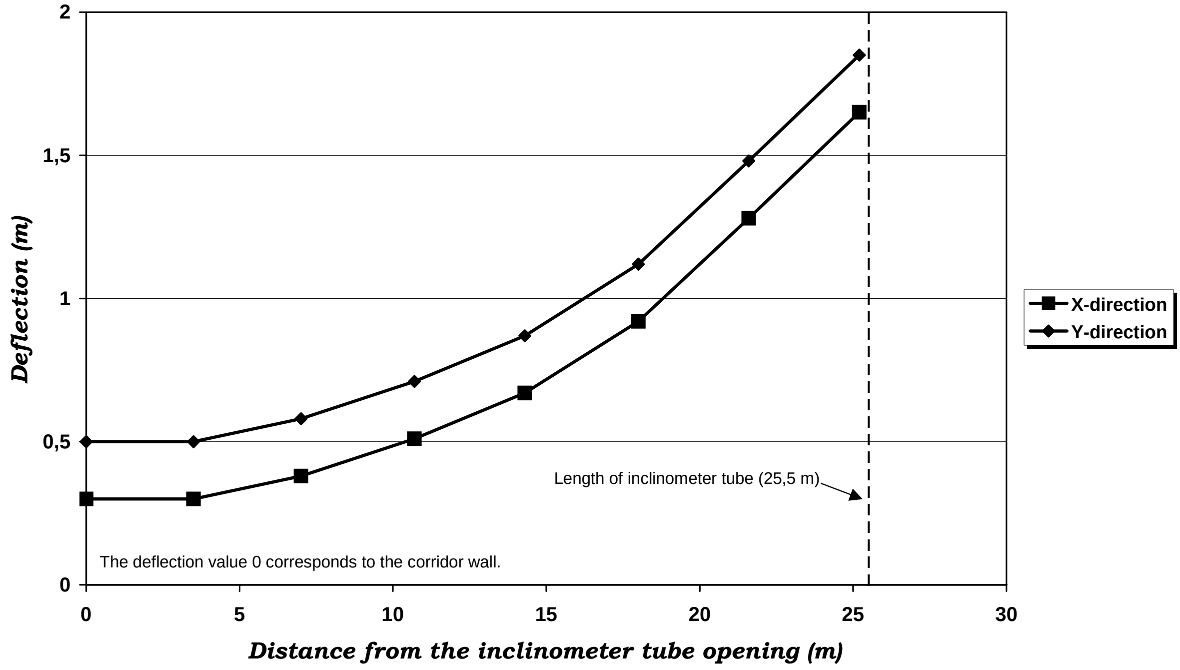


Figure 5.11 Shape-3 for tests with horizontal inclinometer tube. X- and Y-directions correspond to vertical and horizontal directions, respectively.

5.3.2.1 The manual inclinometer

The main reasons for carrying out tests with the manual inclinometer system in the horizontal tube were

- to explore the torsion rigidity of the aluminium rods which are attached to the probe to lower it into the inclinometer tube to the respective measurement levels
- to examine the repeatability of the method.

Questions have been raised as to whether the rigidity of the rods, especially for measurement levels deep below the ground surface, actually is sufficient to ensure an accurate positioning of the probe. The probe is rotated several times during operation and there was a certain concern that unacceptably large errors are introduced.

Two separate tests were carried out for each shape of the inclinometer tube. Only Shape 1 and Shape 3 were used in the tests. Shape 2 was excluded. A total of four tests were carried out. The operation of the inclinometer and the test procedure was, as much as possible, kept to normal field conditions. However, due to the horizontal orientation of the test equipment, it was not possible to measure the inclination of the probe, e.g. the deflection of the inclinometer tube. The positioning of the probe before measuring could not be done as in the field. Normally, some well defined and visible object in the distance is used for the initial positioning of the equipment. At each level of measurement, the direction of the inclinometer probe is set with reference to this initial position. As objects in the distance hardly can be found in a cellar corridor, the positioning of the manual probe was, in fact, somewhat problematic. To make positioning easier, a cut at the front end of the tube was done which could be aimed at when inserting the probe. Nevertheless, all possible efforts were made during the tests to provide as accurate results as possible. Measurements were carried out pair-wise in two orthogonal directions (Y^+, Y^-, X^+, X^-). The actual direction of the inclinometer probe at different distances was measured through the transparent inclinometer tube with reference to the ink lines drawn on the periphery of the tube, and then re-calculated to a corresponding angular deviation from the intended direction of measurement. The result is shown in Table **5.1**.

At a first glance at the results in Table **5.1**, a deviation between the actual and the intended direction of installation can be noticed in all cases. It seems as if the magnitude of this deviation depends of the shape of the inclinometer tube as they, in general, are larger for Shape 3 than for Shape 1. However, it should be kept in mind that the installation procedure was different than normal field conditions during the tests. The result might be an effect of an "inaccurate" positioning of the inclinometer probe already when it was inserted into the inclinometer tube. If this is the case, a continued deviation from the intended direction would, of course, be noticed.

Table 5.1 *Deviation [°] from the intended direction of measurement for the manual inclinometer. Tests with horizontally oriented inclinometer tube.*

Deflection of the inclinometer tube following Shape 1.

Z [m]	**Deviation +Y** [°]			**Deviation –Y** [°]		
	Test 1	**Test 2**	**Average**	**Test 1**	**Test 2**	**Average**
25.66	7	5	6	7	6	6.5
22.66	7	6	6.5	7	5	6
17.66	6	3	4.5	8	5	6.5
12.66	5	2	3.5	5	5	5
7.66	5	2	3.5	6	3	4.5
2.66	2	1	1.5	2	3	2.5
-0.34	2	1	1.5	2	3	2.5

Z [m]	**Deviation +X** [°]			**Deviation –X** [°]		
	Test 1	**Test 2**	**Average**	**Test 1**	**Test 2**	**Average**
25.66	7	6	6.5	7	5	6
22.66	7	5	6	7	6	6.5
17.66	8	5	6.5	5	2	3.5
12.66	5	5	5	2	3	2.5
7.66	5	3	4	2	2	2
2.66	5	2	3.5	2	1	1.5
-0.34	2	1	1.5	2	3	2.5

Deflection of the inclinometer tube following Shape 3.

Z [m]	**Deviation +Y** [°] **Test 1**	 **Test 2**	 **Average**	**Deviation –Y** [°] **Test 1**	 **Test 2**	 **Average**
25.6	11	11	11	14	11	12.5
21.6	11	11	11	11	11	11
17.6	11	9	10	11	10	10.5
13.6	11	11	11	*	*	--
9.6	10	10	10	*	*	--
5.6	11	13	12	*	*	--
0.6	9	10	9.5	*	*	--
Z [m]	**Deviation +X** [°] **Test 1**	 **Test 2**	 **Average**	**Deviation –X** [°] **Test 1**	 **Test 2**	 **Average**
25.6	11	11	11	11	14	12.5
21.6	11	13	12	13	11	12
17.6	11	13	12	9	9	9
13.6	11	11	11	11	11	11
9.6	14	11	12.5	11	11	11
5.6	9	10	9.5	11	11	11
0.6	9	9	9	10	10	10

* For practical reasons, measurements could not be completed.

A more accurate way to analyse the result in Table **5.1** would be to compare the difference in deviation between the first (closest to the opening of the tube) and last (closest to the bottom of the tube) position. For Shape 1 of the inclinometer tube, this difference is about 5° and for Shape 3 about 2°.

The test result might reflect an insufficient torsion rigidity of the rods, thus, leading to a deviation between the actual and the intended direction of installation of the probe. If so, an increased deviation with the length of the rod package would be expected, as the effect of insufficient torsion rigidity would be more pronounced the longer the rod package is. Even if the length of the tube in these tests was limited there is, nevertheless, a trend of increasing deviations with length. It should be pointed out, however, that a horizontal orientation of the inclinometer probe does not correspond to standard procedure and field-like operational conditions. The probe itself is not symmetrical in the axial direction due to the steering knobs and the external plate spring. Gravity effects could maybe have contributed to the test result, but on the other hand, as the weight of the probe itself is quite low compared to the weight of the rod package, such an influence also, in fact, indicates an insufficient rigidity. Therefore, tests in vertical inclinometer tubes were found necessary at this point.

5.3.2.2 The automatic inclinometer

There were mainly three aspects of interest to explore in the horizontal tests with the automatic inclinometer system:

- the rigidity of the inner system (the deviation of individual probes from the intended direction of installation)
- the influence of the type of connection between the distance rods and the inclinometer probe on the deviation that might occur
- the repeatability of the system

It has been mentioned in previous sections that the type of connection between the rods and the probe used so far (slit and tube clamp) might be insufficient and allow for rotation of the individual probes during installation. Therefore, tests were carried out with both this type of connection and a new proposed connection with pre-drilled holes and stop screws.

Furthermore, it has also been suggested that the inner system, as such, is too rigid, and that stresses, in fact, are built up during installation. These stresses are gradually relaxed during a time after completed installation, giving rise to somewhat unexpected or suspicious measurement results. In order to reduce the rigidity and allow for moment free connections, some tests were carried out with a joint mounted between the probes and the distance rods. The complete test program is shown in Table **5.2**

Table 5.2 Test program for the automatic system in the horizontal inclinometer tube. The plate spring direction is given with reference to the positive y-axis, i.e, 0°, which corresponds to an upward direction. For test numbers denoted (s) the rotation of the inclinometer probes have been continuously measured throughout the entire installation process.

Test No.	Rod material	No. of probes	Joint	Screw connection	Tube shape	Direction of plate spring
1A	Glass fiber	15	No	No	1	90°
1B	Glass fiber	15	No	No	1	0°
1C	Glass fiber	15	No	No	1	180°
2A	Glass fiber	15	No	No	2	0°
3A	Glass fiber	15	No	No	3	0°
3B	Glass fiber	15	No	No	3	0°
3C	Glass fiber	15	No	No	3	0°
3D	Glass fiber	15	No	No	3	0°
3E	Glass fiber	15	No	No	3	0°
5A	Glass fiber	15	Yes	Yes	3	0°
5B	Glass fiber	15	Yes	Yes	3	0°
5C	Glass fiber	15	Yes	Yes	3	0°
5D	Glass fiber	15	Yes	Yes	3	0°
5E	Glass fiber	15	Yes	Yes	3	0°
3D(s)	Glass fiber	15	No	No	3	0°
3E(s)	Glass fiber	15	No	No	3	0°
5A(s)	Glass fiber	15	Yes	Yes	3	0°
5B(s)	Glass fiber	15	Yes	Yes	3	0°

An inner system of totally 15 inclinometer probes was used, which is the maximum number possible for the system presently in use at the Swedish Geotechnical Institute. As listed in Table **5.2**, a total of 18 tests were carried out. The actual direction of installation for the 15 inclinometer probes after completed installation was determined in all tests. The final direction of each probe was determined by manual measuring with reference to the ink lines drawn on the periphery of the transparent inclinometer. In four of the tests the rotation of all probes was continuously measured during the entire installation process, i.e. the direction of the probes was followed as they were inserted into the tube – test numbers denoted by (s) in the table above. The direction of the probes was determined also at de-mounting of the inner system in six of the tests.

The complete results from all tests are presented by **Johansson et al. (2001)**. Results for tube Shape 3 are included in this report, Table **5.3**. Shape 1 corresponds to a totally straight inclinometer tube without any deflections at all in any direction. This is really not a very realistic shape, as the inclinometer tubes will normally be deflected to a certain extent during installation in the soil.

Table 5.3 *Angular deviation after completed installation for inclinometer tube Shape 3. In Test No. 3 the old type of connection between the distance rods and the inclinometer probes (slit and tube clamp) was used, and in Test No. 5 the new type (pre-drilled holes and stop screws). In Test No. 5 joints were introduced between the rods and the probes to allow for moment free connections. The final direction of the inclinometer probes was measured from the positive y-axis corresponding to 0°, or an upward direction. The z co-ordinate is along the inclinometer tube.*

Deflection of the inclinometer tube following Shape 3.
Connection between probe and distance rod with slit and tube clamp.

Z [m]	**Test No. 3A** [°]	**Test No. 3B** [°]	**Test No. 3C** [°]	**Test No. 3D** [°]	**Test No. 3E** [°]	**Average** [°]
22.58	2	11	5	30	11	11.8
19.62	-5	7	2	25	5	6.8
16.62	-8	7	0	18	1	3.6
14.63	-9	13	7	26	2	7.8
13.63	-11	14	5	24	2	6.8
12.63	-14	14	-2	21	-5	2.8
11.64	-11	14	0	25	0	5.6
10.65	2	13	-2	26	6	9
9.65	2	11	1	27	7	9.6
8.66	-1	-1	-3	22	3	4
7.67	-5	-2	-9	23	6	2.6
6.67	-1	-2	-9	21	6	3
5.67	2	5	-10	15	6	3.6
4.67	8	5	-9	8	0	2.4
3.67	2	2	-9	5	-3	-0.6

Deflection of the inclinometer tube following Shape 3.
Connection between probe and distance rod with pre-drilled hole and stop screw.

Z [m]	**Test No. 5A** [°]	**Test No. 5B** [°]	**Test No. 5C** [°]	**Test No. 5D** [°]	**Test No. 5E** [°]	**Average** [°]
22	-8	6	-7	-7	-7	-4.6
19	-7	2	-8	-8	-11	-6.4
16	-1	7	-5	-5	-7	-2.2
14	-7	2	-9	-11	-9	-6.8
13	-8	-1	-11	-13	-11	-8.8
12	-3	5	-5	-8	-7	-3.6
11	-9	-1	-10	-14	-11	-9
10	-8	0	-8	-13	-11	-8
9	-5	3	-7	-9	-6	-4.8
8	-6	5	-5	-7	-5	-3.6
7	-5	6	-2	-5	-3	-1.8
6	-3	5	-5	-7	-3	-2.6
5	-6	9	1	0	3	1.4
4	-3	11	1	-2	0	1.4
3	-7	7	-1	-5	-1	-1.4

It is evident that the inclinometer probes in all tests have deviated (rotated) from the intended direction of installation. The deviation seems to vary between the individual probes and also to be dependent on the shape – deflection – of the inclinometer tube. There is an indication that the deviation increases monotonously with installation length for the old system, while the rotation seems to be arbitrary in both directions around the intended direction of installation for the new type of connection. The inner system was examined after de-mounting in order to reveal rotations that might have occurred in the connection between the probes and the distance rods. Quite surprisingly, though, no such evidence of rotations could be noticed.

In six of the tests not only the direction of the inclinometer probes after completed installation was measured, but also the position at de-mounting when the respective inclinometer left the inclinometer tube. The result is presented in Table **5.4**.

Table 5.4 *Comparison between the deviation from the intended direction of installation (rotation) after completed installation and at de-mounting.*

Test No. 1A

Z [m]	**Rotation In** [°]	**Rotation Out** [°]
22.36	122	144
19.37	117	144
16.36	112	142
14.36	109	119
13.36	102	107
12.37	96	98
11.37	81	78
10.37	69	66
9.38	67	67
8.38	57	56
7.38	48	54
6.39	50	53
5.39	41	37
4.39	33	31
3.39	24	13

Test No. 1B

Z [m]	**Rotation In** [°]	**Rotation Out** [°]
22.40	0	2
19.41	-3	18
16.40	-2	14
14.40	0	16
13.41	-2	14
12.41	-11	6
11.41	-14	-5
10.41	-14	-8
9.41	-14	-7
8.42	-14	-9
7.42	-13	-9
6.43	-10	-3
5.43	-8	-3
4.43	-11	0
3.43	-11	-7

Test No. 1C

Z [m]	**Rotation In** [°]	**Rotation Out** [°]
22.43	56	146
19.44	55	133
16.44	73	151
14.44	72	144
13.44	71	130
12.44	57	111
11.44	48	96
10.44	43	82
9.44	39	66
8.44	25	46
7.45	11	27
6.46	7	16
5.46	7	9
4.46	5	7
3.46	0	0

Test No. 2A

Z [m]	**Rotation In** [°]	**Rotation Out** [°]
22.24	34	7
19.27	32	-10
16.27	32	-18
14.27	41	11
13.28	38	14
12.28	31	2
11.28	29	0
10.29	35	13
9.29	35	23
8.3	30	22
7.3	25	16
6.3	24	18
5.31	24	16
4.31	46	16
3.31	16	15

Test No. 1C

Z [m]	**Rotation In** [°]	**Rotation Out** [°]
22.43	56	146
19.44	55	133
16.44	73	151
14.44	72	144
13.44	71	130
12.44	57	111
11.44	48	96
10.44	43	82
9.44	39	66
8.44	25	46
7.45	11	27
6.46	7	16
5.46	7	9
4.46	5	7
3.46	0	0

Test No. 2A

Z [m]	**Rotation In** [°]	**Rotation Out** [°]
22.24	34	7
19.27	32	-10
16.27	32	-18
14.27	41	11
13.28	38	14
12.28	31	2
11.28	29	0
10.29	35	13
9.29	35	23
8.3	30	22
7.3	25	16
6.3	24	18
5.31	24	16
4.31	46	16
3.31	16	15

The maximum rotation noticed after complete installation was 122° (Test No. 1A), and in connection with de-mounting 146° (Test No. 1C), Table **5.3**. The final direction of the inclinometer probe in these particular tests was thus almost opposite to the intended direction. However, in most cases the rotation was found to be substantially smaller, mostly between 14° and 30° for the old type of connection between the distance rods and the inclinometer probes and, in principle, between 5° and 10° for the new type.

The results from the tests in which the rotation of the probes were measured throughout the entire installation process verify the monotonous increase in deviation from the intended direction with installation length for the old type of connection between the probes and the distance rods, Table **5.5**. For the new type of connections, the deviation tends to vary arbitrarily in both directions around the intended installation direction.

Table 5.5 *Continuous measurement during the installation process of the deviation from the intended direction (rotation) for a selection of inclinometer probes. In Test No. 3 the old type of connection between the distance rods and the probes (slit and tube clamp) was used, while the new type (pre-drilled hole and stop screw) was used in Test No. 5. The z co-ordinate in the table refers to the final position for the respective probe in the tube.*

Test No. 3D

Reading No.	**Rotation Probe No. 231 [z=22.58]**	**Rotation Probe No. 169 [z=14.0]**	**Rotation Probe No. 152 [z=9.0]**
1	0		
2	3		
3	7		
4	14		
5	0	0	
6	2	-5	
7	5	-1	
8	7	-1	
9	3	-1	
10	5	1	0
11	9	5	5
12	9	5	5
13	9	2	2
14	19	14	14
15	18	14	16
16	25	21	23
17	23	16	22
18	30	26	27

Test No. 3E

Reading No.	**Rotation ProbeNo. 231 [z=22.58]**	**Rotation Probe No. 169 [z=14.0]**	**Rotation Probe No. 152 [z=9.0]**
1	0		
2	-1		
3	5		
4	8		
5	7	0	
6	7	-7	
7	11	-2	
8	9	-5	
9	5	-7	
10	2	-9	0
11	7	-5	0
12	7	-6	-2
13	5	-8	-7
14	8	-3	0
15	15	5	9
16	14	2	7
17	9	-1	5
18	11	2	7

Test No. 5A

Reading No.	**Rotation Probe No. 231 [z=22.58]**	**Rotation Probe No. 169 [z=14.0]**	**Rotation Probe No. 152 [z = 9.0]**
1	0		
2	0		
3	-6		
4	-2	-1	
5	0	1	
6	0	-1	
7	5	5	
8	3	5	
9	0	1	-1
10	0	1	0
11	-2	0	0
12	1	2	3
13	1	2	3
14	0	1	2
15	-2	0	1
16	0	1	0
17	-2	-1	-2
18	-8	-7	-5

Test No. 5B

Reading No.	**Rotation Probe No. 231 [z=22.58]**	**Rotation Probe No. 169 [z=14.0]**	**Rotation Probe No. 152 [z=9.0]**
1	0		
2	1		
3	-2		
4	2	0	
5	5	2	
6	0	-3	
7	7	3	
8	2	-1	
9	7	6	3
10	-5	-7	-9
11	-3	-5	-2
12	3	0	-1
13	-7	-9	-8
14	-6	-9	-7
15	-6	-9	-6
16	7	3	5
17	9	5	7
18	6	2	3

As for the manual inclinometer system, some of the deviations noticed during the tests might, of course, be possible to explain by the fact that they were carried out with horizontal inclinometer tubes. Even so, it is evident that the system, as such, allows for unacceptable deviations from the intended direction of installation.

5.3.2.3 Conclusive remarks

The amount of data available from the horizontal tests is still limited in order to draw any definite conclusions. However, the following indications have been obtained:

- For the *automatic system* it seems as if the angular deviations increase monotonously and also with fairly large magnitude for the old type of connection between the distance rods and the probes (slit and tube clamp). For the new type of connection (pre-drilled holes and stop screws) the angular deviations seem to occur arbitrarily in both directions around the intended direction of installation.
- The magnitude of the deviations from the intended direction of installation is smaller for the new type of connection than for the old type.
- Inspection after de-mounting of the inner system did not reveal any rotations at the connections between the distance rods and the inclinometer probes. Therefore, the origin of the rotation or the deviation from the intended direction of installation must be sought within the inner system itself.
- For the *manual inclinometer* the deviations between the actual and the intended direction of measurement are small, in general. The deviations seem to increase somewhat monotonously with depth below the ground surface, which might be an indication of insufficient torsion rigidity of the aluminium rods used to lower the probe in the inclinometer tube.
- For both the *manual* and the *automatic* system, there are some indications that the deflection (the shape of the inclinometer tube) has a certain influence on the magnitude of the deviation from the intended installation direction.
- For both the *manual* and the *automatic* system, the results from repeated tests did not differ significantly. The horizontal tests, accordingly, indicate a satisfactory repeatability for both systems.

The deviation from the intended direction of installation seems to be in the same direction with the old type of connection, and also increasing monotonously with the length of the inner system, or with the number of inclinometer probes. This result indicates the occurrence of systematic errors. As a last step of the horizontal tests, the distance rods of the automatic system were carefully examined in an attempt to find possible sources of systematic errors.

For the old type of connection, it was found that the tolerance for the location of the slit in each end of the distance rods was unacceptable. While the slits on each side of the distance rod, of course, should be exactly opposite to each other, it was concluded that there was an angular deviation of between 3° and 9° between them, and occurring in the same direction all the time. When the inner system is assembled all probes will be rotated with reference to each other in the same direction and, in principle, by the same amount. In the worst case, with an inner system consisting of the maximum possible number of 15 probes, the direction of installation of the lowermost inclinometer might be rotated as much as 130° compared to that of the uppermost one. When each probe is inserted in the inclinometer it is positioned by aiming at a cut at the top of the inclinometer tube. The uppermost probe is thus most likely to be positioned correctly, i.e. in the direction of measurement. On the other hand, in the worst case, the lowermost probe might then be rotated up to 130° from the direction of measurement. In addition to these deviations due to insufficient tolerances of the slit on the distance rods, additional rotation of the probes might occur during installation.

A similar examination of the distance rods used with the new type of connection, i.e. with a pre-drilled hole at each end, was also done. Until then, distance rods, which the Swedish Geotechnical Institute used had been ordered ordered. It was found that the tolerance in the position of the pre-drilled hole was about 5° in arbitrary directions. This level of tolerance was also concluded to be unsatisfactory, which is why the Swedish Geotechnical Institute began to manufacture distance rods for the automatic system in their own workshop giving a tolerance of approximately 1° for the pre-drilled holes, which must be considered as acceptable.

5.3.3 Tests in inclinometer tubes installed in rock

The main aims with the tests in inclinometer tubes installed in rock were

- to explore the repeatability of the systems through several consecutive installations (measurements)
- to explore the long term stability of the automatic system. As no horizontal movements would be expected for inclinometer tubes installed in rock, the measurements should obviously give almost zero values as result.

Two bore-holes were drilled in the rock not far from the office building of the Swedish Geotechnical Institute in Linköping. One bore-hole was drilled as straight and vertical as possible and with a length of 33 m; in the following denoted Hole 1, and one deliberately inclined, as much as practically possible with reference to the drilling operation, with a length of 35 m; in the following denoted Hole 2. The space between the inclinometer tube, which was of conventional type, and the surrounding rock was grouted to ensure satisfactory contact.

Before the inner systems with automatic inclinometer probes were installed, the shape and actual inclination of the inclinometer tubes were determined with the manual inclinometer (zero reading). Another such measurement was carried out after the inner system was de-mounted the first time (follow up reading).

5.3.3.1 The manual inclinometer

Standard procedures for the operation of the manual inclinometer were followed during the tests. These are outlined in the introductory sections of this chapter.

Totally five measurements (including the zero reading) were carried out prior to the first installation of automatic systems. Another measurement was carried out between the first and the second installation of the automatic system (follow up reading).

The evaluated horizontal movements in the X- and Y-directions, respectively, are shown in **Figure 5.12**. Contrary to what would have been expected, horizontal movements were, in fact, measured, both in the X- and in the Y-direction. The maximum magnitude is on the order of 3 to 4 mm during the actual time period, a little less than a year. The measurements would obviously lead to conclusions that horizontal movements do occur. The magnitudes of the movements vary somewhat arbitrarily between the different measurements. It is difficult to find any distinct pattern in the result, why it is challenging to conclude that the accuracy of the system would probably be in the range of a couple of mm per year, maybe up to three or four mm. Considering, however, that a common rate of movement in typical Swedish clay slopes would be in the same range or maybe a little more, the result becomes somewhat worrying.

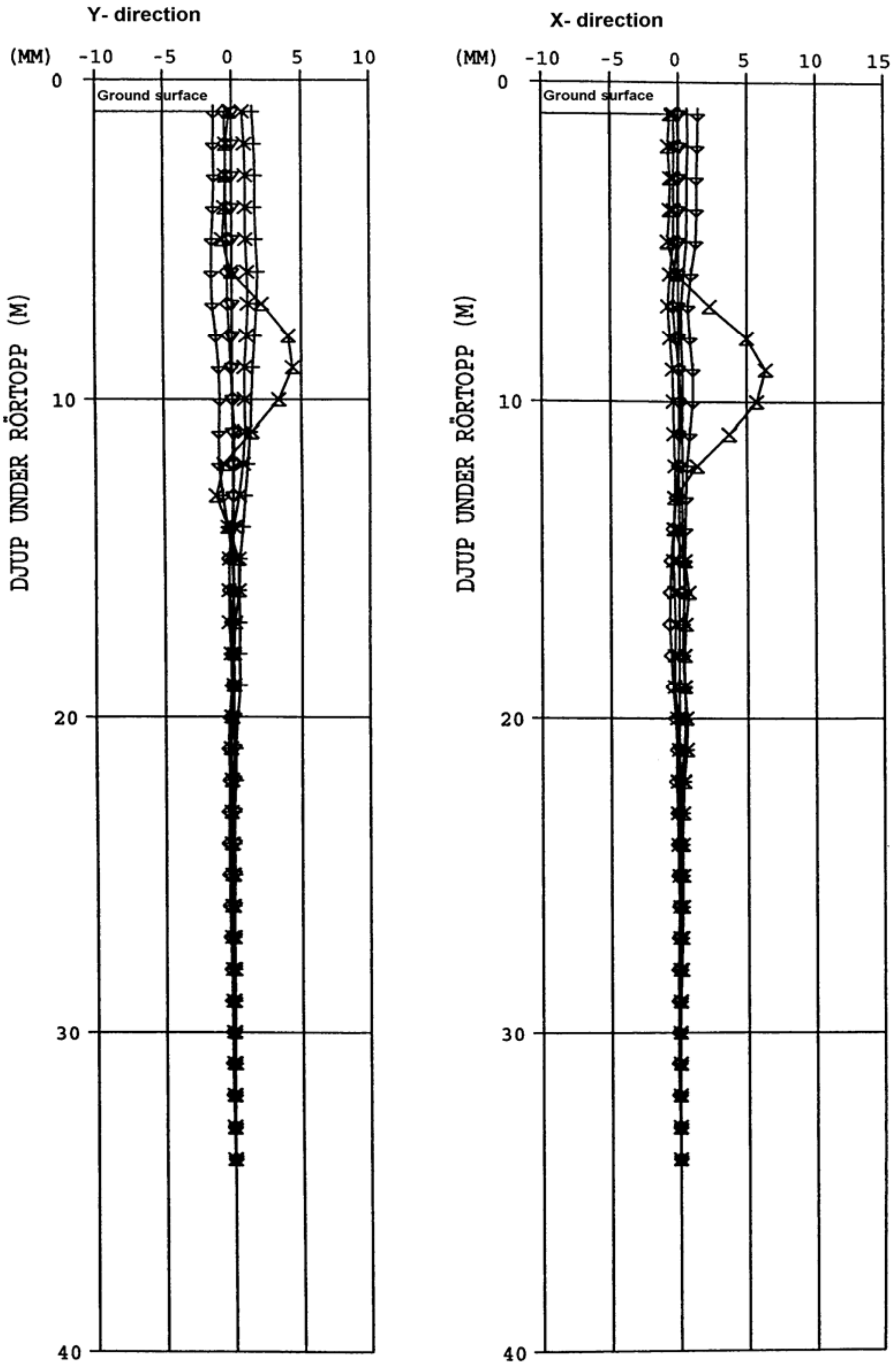


*Figure **5.12** Results from measurements with the manual inclinometer in Bore-hole No. 2 (inclined) in rock.*

5.3.3.2 Automatic inclinometers

The standard procedure for installation and operation of the automatic system, as outlined in the introductory sections of this chapter, was followed during the tests.

An inner system of 15 inclinometer probes was used in each of the two bore-holes. After installation, measurements continued either until stabilised values were obtained, i.e. values of the inclination, which did not change with time, or alternatively until it was decided to interrupt the test. The inner system was then de-mounted, malfunctioning components, if any, were replaced, and the inner system was re-installed into the inclinometer tube. This procedure was repeated five times.

For the inner system used in the straight bore-hole (Bore-hole No.1), the distance between each of the nine lowermost probes was 3 m, between the following probes 2 m, and between the remaining four probes the distance was 1 m.

In the inclined bore-hole, an inner system was used with a distance of 3 m between each of the six lowermost probes, a distance of 2 m between the following four probes, and between the remaining five probes the distance was 1 m.

The first installation was in operation for a total of 22 days. An example of the results, for Bore-hole No. 2, is shown in **Figure 5.13**. The complete result is found in **Johansson et al. (2001)**.

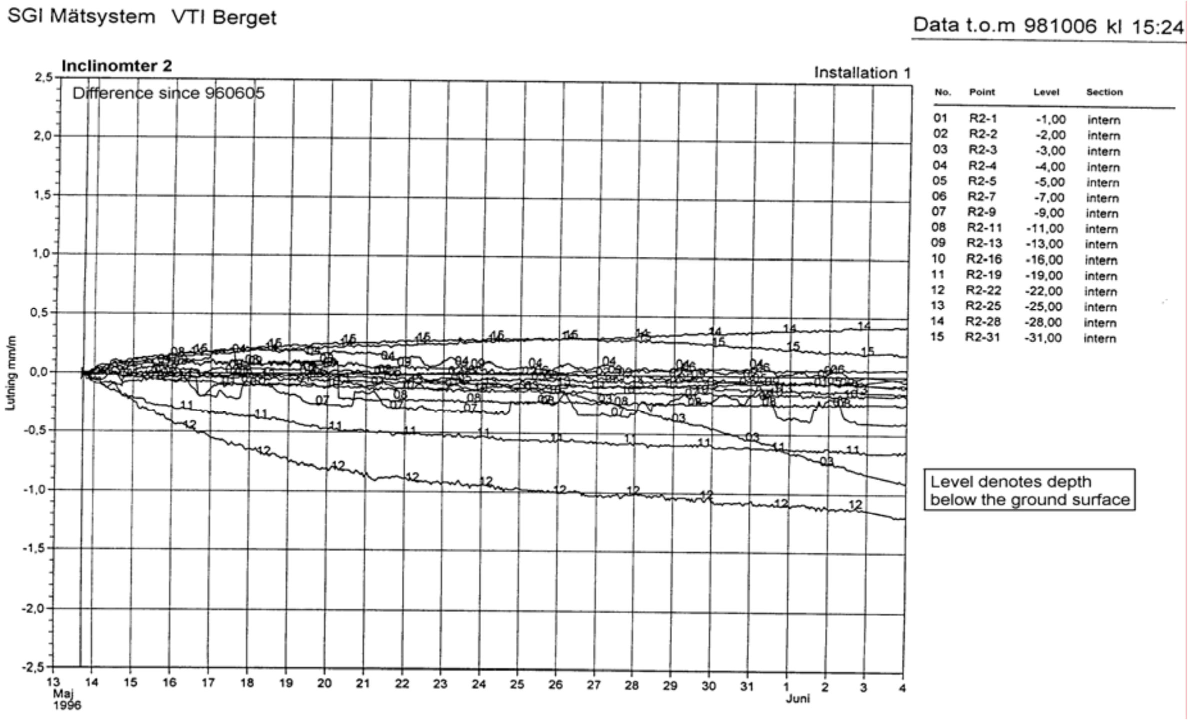


*Figure **5.13** Inclination (mm/m) vs. time for Bore-hole No. 2 (inclined) in rock during the first installation with the automatic system.*

As can be seen from **Figure 5.13**, there seems to be an initial adaptation period of about 10 days during which the rate of inclination is increasing for all probes. In general, there were no significant differences in result between Bore-hole No.1 and Bore-hole No.2, neither for the trend of the inclinations, nor for the magnitudes of the inclinations. In both bore-holes, most probes eventually produced somewhat stabilised values of the inclination of about 0.5 mm/m. However, a remarkable result for both bore-holes was that several probes did not produce stabilised values even when the test was terminated. Many probes showed a slow, but steady increased rate of inclination. Likewise for both bore-holes there were a couple of inclinometer probes which produced unrealistic results, indicating malfunction.

The second installation was in operation for a total of 84 days. An example of the results, for Bore-hole No. 2, is shown in Figure **5.14**.

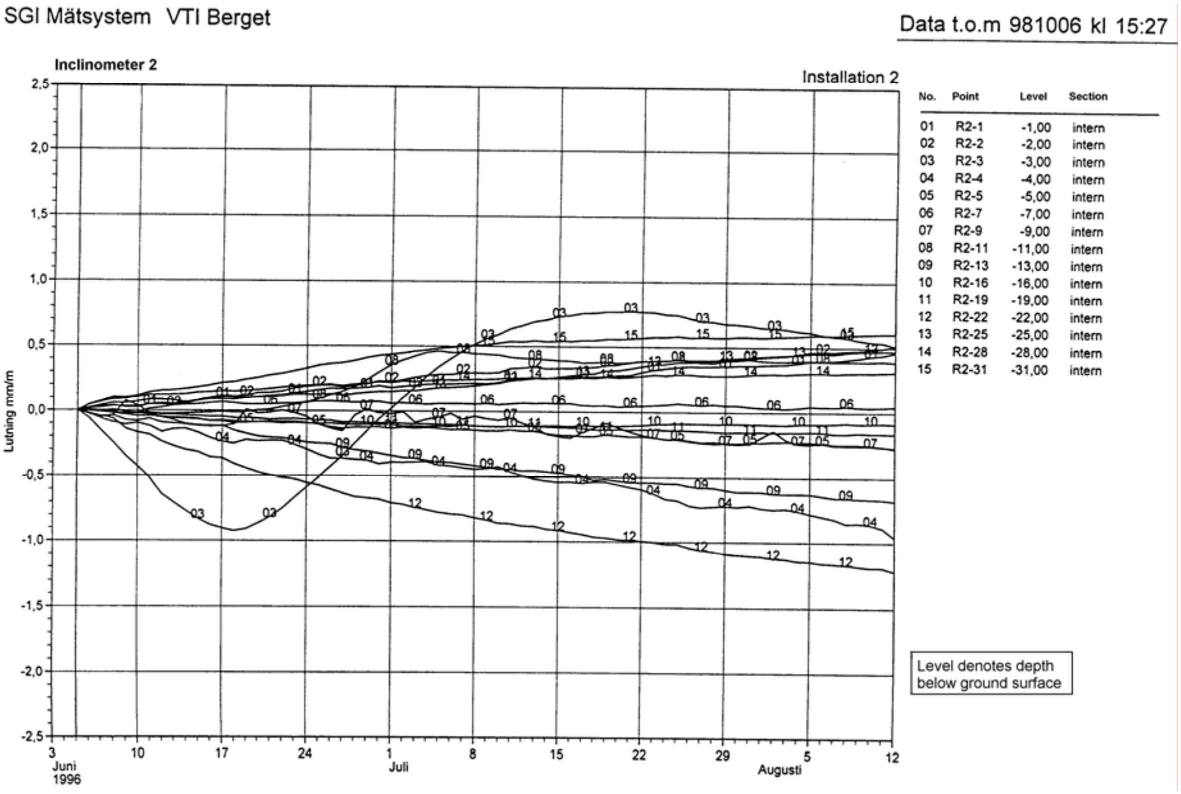


Figure ***5.14*** *Inclination (mm/m) vs. time for Bore-hole No. 2 (inclined) in rock during the second installation with the automatic system.*

As in the first installation, there seems to be an initial period of adaptation, even if there is no such distinct "breaking point" as could be observed in the first installation. It also seems as if this adaptation period lasts somewhat longer during the second installation, obviously around a month. The maximum value of the inclination is also somewhat larger during the second installation, about 1 mm/m, compared to half that value for the first installation. The significant difference compared to the first installation is that most probes during the second installation still did not produce stabilised values after completion of the test. Several probes showed a remarkably high rate of inclination, especially taking into account that no horizontal movements are expected in the rock mass. As during the first installation, certain probes gave somewhat unrealistic results, indicating either malfunction or some kind of installation effect, e.g. some kind of interaction between the inner system and the inclinometer tube.

The third installation was in operation for a total of 316 days. Complete sets of new inclinometer probes were used in order to eliminate any malfunctions. The result, however, is somewhat difficult to analyse. The measurements were disrupted three times. Once due to the theft of the computer used to register and record measurement data, and once due to a large grass fire, which unfortunately destroyed most of the cables. Generally, the same trends as for the previous installations could be noticed, i.e. an initial adaptation period with large rates of inclination which tended to be reduced after roughly 30 days. However, the observed pattern and trends of inclinations changed each time the measurements were disrupted. It is quite difficult to know the reason for this. No changes would be expected to occur, at least not after the replacement of the stolen computer. On the other hand, it is not unlikely that some electronic faults occurred in connection with the fires destroying the cables. Nevertheless, all explanations would be rather hypothetical. More important is the conclusion that, in fact, none of the probes produced stabilised values at the end of the test period, i.e. after almost a year. Furthermore, the maximum measured inclinations were considerably larger than for any of the previous installations; for certain probes 1.5 to 2.0 mm/m. Except for the interesting condition that the installation period was fairly long, the result, as such, must be looked upon as somewhat suspicious. The reader is referred to **Johansson et al. (2001)** for further details.

The fourth installation was in operation for a total time of 42 days. An example of the results, from Bore-hole No. 1, is shown in **Figure 5.15**. Compared to previous installations, some basic features were changed for this one:

- a number of joints were included in the connections between some of the probes and distance rods
- the inclined inclinometer tube (Bore-hole No. 2) was lubricated with bentonite prior to installation of the inner system in order to minimise the friction between the inner system and the inclinometer tube.

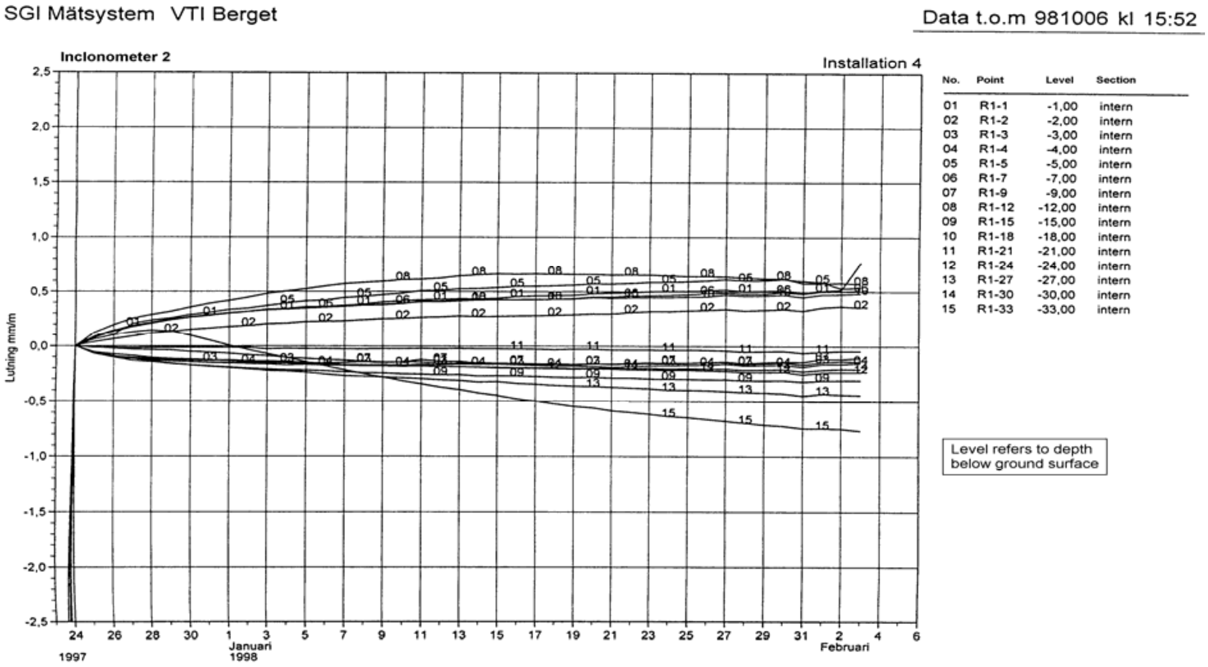


Figure ***5.15*** *Inclination (mm/m) vs. time for Bore-hole No. 1 (straight) in rock during the fourth installation with the automatic system.*

The same pattern as with previous installations is observed, i.e. an initial adaptation period of 20 – 30 days with fairly high rates of inclinations whereby the probes tend to produce stabilised values. A few probes show a low rate of inclination throughout the total period of installation, and, as in all installations so far, one or two probes show unrealistic results, indicating malfunction. The maximum magnitude of inclination is about 0.5 mm/m, agreeing with the results from the first installation. No distinct effects from introducing joints between some probes and the distance rods, or from lubricating the inclinometer tube can be noticed.

Finally, the fifth installation was in operation for a total of 205 days. An example of the results, from Bore-hole No. 2, is shown in **Figure 5.16**.

The same patterns and trends as with the previous installations are observed also during this last installation. There is, once again, an initial period of adaptation during which the rate of inclination increases. After about 20 to 30 days, the rate of inclination decreases. While most probes produce stabilised measurement values, i.e. no or at least a very low rate of inclination after this "breaking point", a few probes still show a fairly high rate of inclination throughout the entire time of installation. Compared to previous installations, a larger number of probes indicate malfunctioning by presenting unrealistic results.

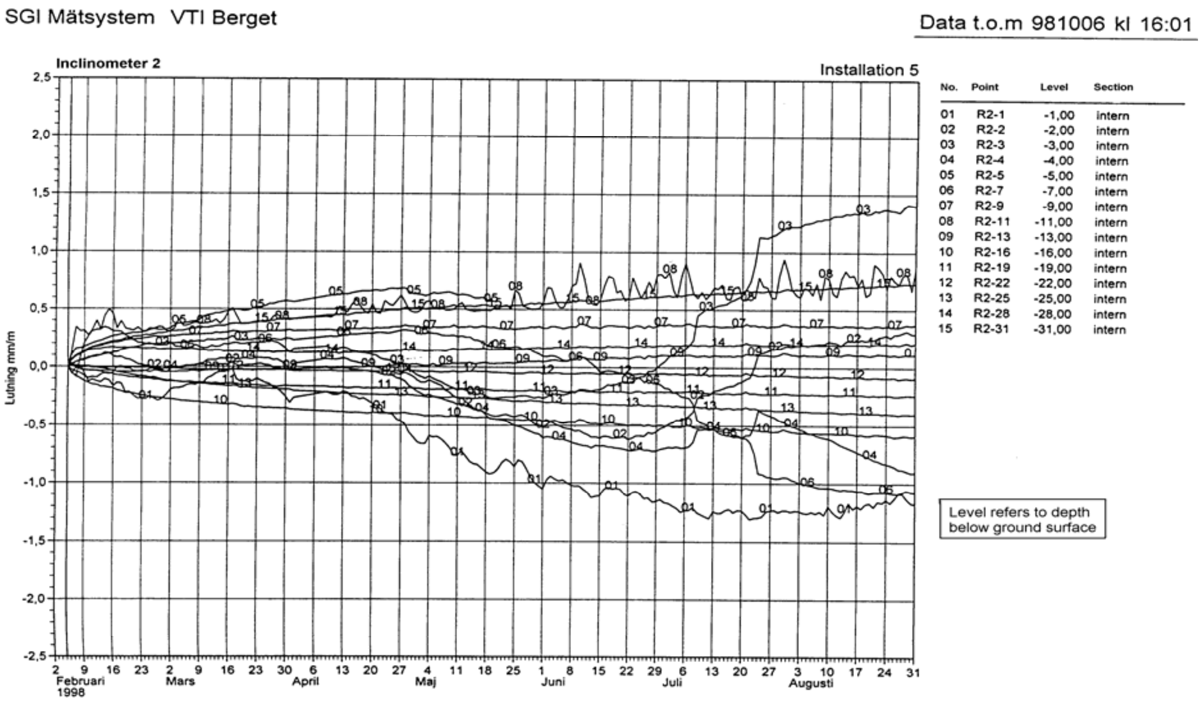


Figure ***5.16*** *Inclination (mm/m) vs. time for Bore-hole No. 2 (inclined) in rock during the fifth installation with the automatic system.*

5.3.3.3 Conclusive remarks

Starting with the automatic system, the tests seem to verify the existence of an adaptation period, during which the inner system (the assembly of inclinometer probes, cables, and distance rods) in some way adjusts itself to the outer system (the inclinometer tube). The reason for this adaptation period is not known, and obtained results do not give any further guidance for interpretation. Any kind of guess would be hypothetical. However, it is reasonable to believe that a certain amount of stress is built up within the inner system during the installation phase, especially for systems of somewhat larger length. These stresses are gradually being relaxed during a period after the completion of the installation phase, giving rise to the adaptation period being possible to notice in the measurement result. For the installations carried out within these tests, the period of adaptation seems to last for about 30 days. However, for other conditions than those of these tests, it can not be excluded that the adaptation period can be both longer and shorter.

There is no significant difference in results from measurements in the straight bore-hole (No. 1) and in the inclined bore-hole (No. 2). The measured rates of inclination in both bore-holes are remarkably high considering that the inclinometer tubes were installed in rock where no movements at all, or at least movements of negligible magnitude, can be expected.

Certain probes also show a significant rate of inclination after a fairly long time – half a year or so. This result might indicate a drift in the electronic components.

Introducing joints between the inclinometer probes and the distance rods to allow for moment-free connections does not seem to have any major influence on the performance. Neither does lubrication of the inclinometer tube prior to installation of the inner system to reduce friction.

The manual system, on the other hand, shows small values of horizontal movements; a couple of mm during the total measurement period of, in principle, one year, both in the X- and the Y-directions. However, even those few measured mm are remarkable for inclinometer tubes installed in rock. If these tests indicate the actual accuracy of the manual system, the magnitude of the measured horizontal movements should be compared to common rates of movement in typical Swedish clay slopes, which, in fact, often are in the same range.

5.3.4 Tests in vertical inclinometer tubes

The inclinometer evaluation project also included tests in a vertical inclinometer tube, installed on one of the walls in the highest parts of the building hosting the central heating plant in Linköping.

The main aspects investigated during the vertical tests were:

- installation effects, i.e. rotation of the inclinometer probes during the installation phase compared to intended directions of installation
- the ability for the inclinometer systems to capture a known deflection of the inclinometer tube.

The experience gained from the previous horizontal tests were used to optimise the test program for the comparatively more complicated and expensive vertical tests. One of the most important aspects to investigate was if there were any additional factors giving rise to a rotation of the probes during installation other than the unsatisfactory tolerances of the slits and the pre-drilled holes on the distance rods which were discovered at the end of the horizontal tests. Therefore, comparative tests were carried out between an inner system installed in the inclinometer tube in the normal way and a free hanging inner system. The free hanging inner system was obtained by de-mounting the external plate springs on the inclinometer probes before insertion into the inclinometer tube.

The total length of the transparent inclinometer tube, which was of the same type as for the horizontal tests, was 21.5 m. In order to allow for measurements of the rotation of the probes, ink lines were drawn along the periphery of the tube, corresponding to 0°, 90°, 180°, and 270° with reference to a fictitious co-ordinate system on top of the tube. This was the same procedure as adopted in the horizontal tests. Furthermore, the inclinometer tube was mounted on the wall with devices allowing for a controlled deflection of known magnitude at specific points. The installation was done indoors to avoid the influence on the test result of climatic changes as much as possible.

Initially, four different well-defined shapes of the inclinometer tube (deflections) were chosen. However, eventually only three of them came to be used, **Figures 5.17 – 5.19**.

In the figures, the different directions have been separated from each other to make the presentation clearer. The figures should only be used for relative measures of the deflection.

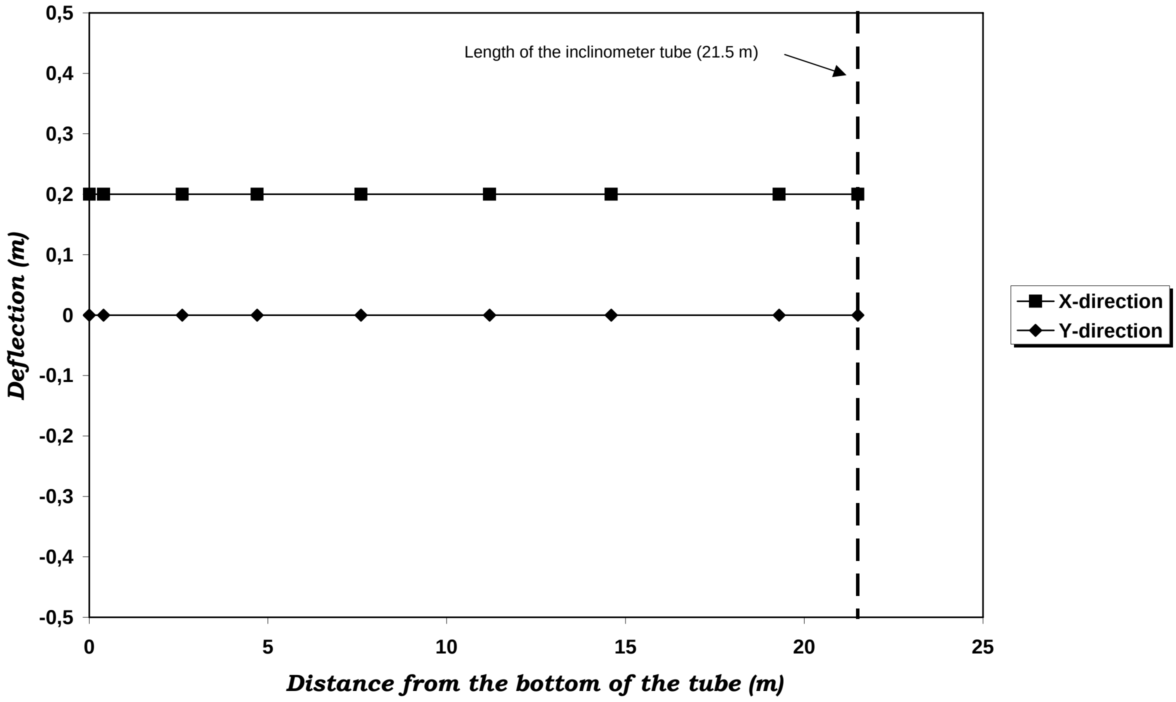


Figure ***5.17*** *Shape-1 for tests with vertical inclinometer tube.*

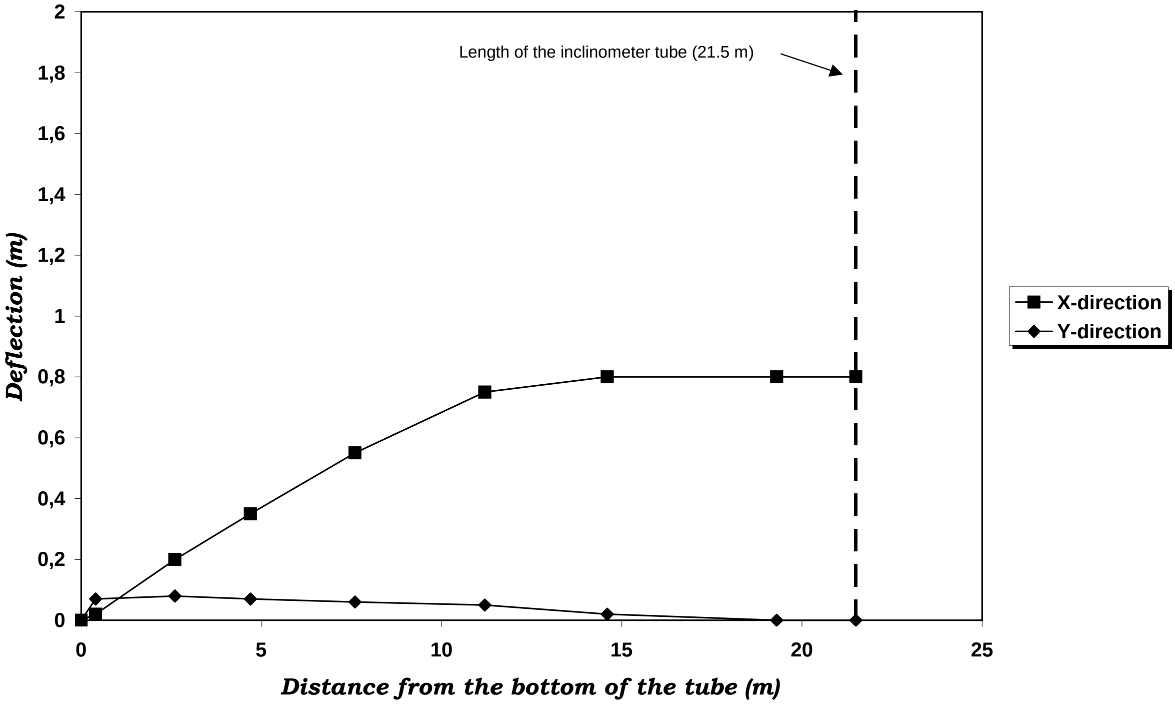


Figure ***5.18*** *Shape-2 for tests with vertical inclinometer tube.*

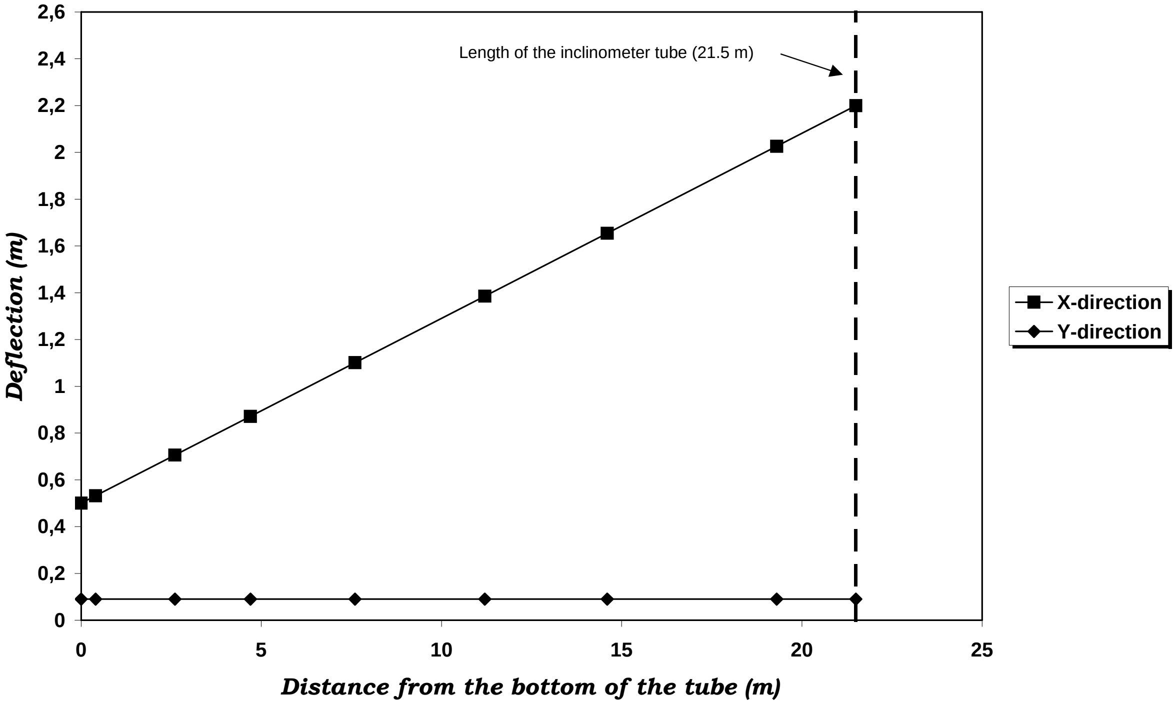


Figure ***5.19*** *Shape-3 for tests with vertical inclinometer tube.*

5.3.4.1 *The manual inclinometer*

Standard procedures for the operation of the manual inclinometer were followed during the tests. These are outlined in the introductory sections of this chapter.

For Shape-1 of the inclinometer tube, six measurements were done. The zero reading was repeated in each case in order to get an indication of the repeatability. The complete test program is shown in Table **5.6**.

Table ***5.6*** *Test program for measurements with the manual inclinometer in vertical inclinometer tube. Peripheral measurement means that the final direction of the inclinometer probes was measured along the periphery of the tube with reference to the ink lines, and then compared to the intended direction of installation. The column "Max. deflection" shows the maximum deflections, at one point, which was caused by adjusting the supports of the inclinometer tube.*

Test No.	**Tube Shape**	**Peripheral measurement**	**Max. deflection** [mm]
1	1	Yes	0
2	1	Yes	0
3	1	-	10
4	1	-	50
5	1	-	100
6	1	-	200
15	2	Yes	0
16	2	Yes	0
17	2	-	10
18	2	-	50
19	2	-	100
20	2	Yes	200
29	3	Yes	0
30	3	Yes	0
31	3	-	10
32	3	-	50
33	3	-	100
34	3	Yes	200

The rotation of the inclinometer probe during installation, compared to the intended direction of measurement, was measured with reference to the ink lines drawn along the periphery of the inclinometer tube. As the tube was mounted on a wall, measurements with the manual inclinometer could, for practical reasons, not be done in all four directions (X^+, X^-, Y^+, and Y^-), only in three of them. Furthermore, the manual inclinometer should, according to the guidelines for operation, be positioned in the tube by aiming at several well-defined objects in a distance away. Even if the tests with the manual inclinometer were supposed to be carried out under conditions as similar as possible to those in the field, the positioning of the probe could not be carried out completely correctly. There was either a lack of suitable objects in a distance away, insufficient visibility for aiming at them, or simply practically impossible to carry out the procedure of positioning the probe because of the test conditions. A similar problem does not apply to the automatic inclinometer system, as the probes are inserted into the inclinometer tube by aiming at cuts on top of the tube. As for the tests in the horizontal inclinometer tube, the absolute value of the measured deviation from the intended direction of measurement should not be paid too much attention to. Instead, the difference between the deviation in installation direction at the first and the last level of measurement, respectively, should be compared. Another way of controlling the quality of the results is to compare several consecutive measurements. Therefore, several parallel measurements were carried out with the manual inclinometer for different maximal deflections of the inclinometer tube. Maximal deflections refer to the known deformation of the tube caused by adjusting the support devices on the wall. Results from measurements of the deviation of the manual inclinometer probe compared to the intended direction of measurement are presented in Table **5.7**.

Table ***5.7*** *Angular deviation of the inclinometer probe from intended direction of measurement. The angle is measured from the vertical centre of the plate spring on the probe and the ink line on the inclinometer tube in the direction +X. With no rotation, this angle would have been 90°. Max deflection is the largest deformation of the inclinometer tube regardless of the shape of the tube during the test. The Z co-ordinate is measured from the bottom of the tube and upwards.*

Tube Shape-1

Z [m]	**Angle between plate spring and ink line in direction +X** [°] **Max. deflection 0 mm** Test No. 1	**Max. deflection 0 mm** Test No. 2
18,56	91	91
14,56	91	91
11,56	91	91
8,56	94	91
4,56	89	89
0,56	94	91

Tube Shape-2

Z [m]	**Angle between plate spring and ink line in direction +X** [°] **Max. deflection 0** Test No. 15	**Max. deflection 0** Test No. 16	**Max. deflection 200** Test No. 20
19,56	93	90	87
14,56	94	93	91
11,56	94	93	91
8,56	94	94	91
4,56	91	91	91
0,56	91	91	91

Tube Shape-3

Z [m]	**Angle between plate spring and ink line in direction +X** [°] **Max. deflection 0** Test No. 29	 **Max. deflection 0** Test No. 30	 **Max. deflection 200** Test No. 34
19,56	75	78	79
14,56	79	80	80
11,56	79	80	80
8,56	82	81	82
4,56	80	81	80
0,56	82	81	81

The difference in deviation between the uppermost and the lowermost level of measurement is, in principle, ± 2° in all tests. Only in one test is the deviation larger, 5°. During the test for tube Shape-3, it was too dark outside to allow for an accurate positioning aiming at an object in a distance away. Therefore, the initial deviation from the intended direction is fairly large. The repeatability seems to be satisfactory on the basis of these test results. It is also evident that the tests in a vertical inclinometer tube give more realistic results than the initial tests in a horizontal tube.

The second part of the test was to measure the inclination of the inclinometer tube, re-calculate it by applying the standard algorithms to horizontal movement, and compare it to the known deflection of the tube. The result is presented in Figures **5.20 – 5.22** for the different shapes of the inclinometer tube.

As can be seen from the figures, it must be concluded that the manual inclinometer manages to capture the actual deflection of the inclinometer tube in a satisfactory way. The differences between the known shape (max. deflection) of the tube and the measured shape are, in general, small, and probably of no practical importance.

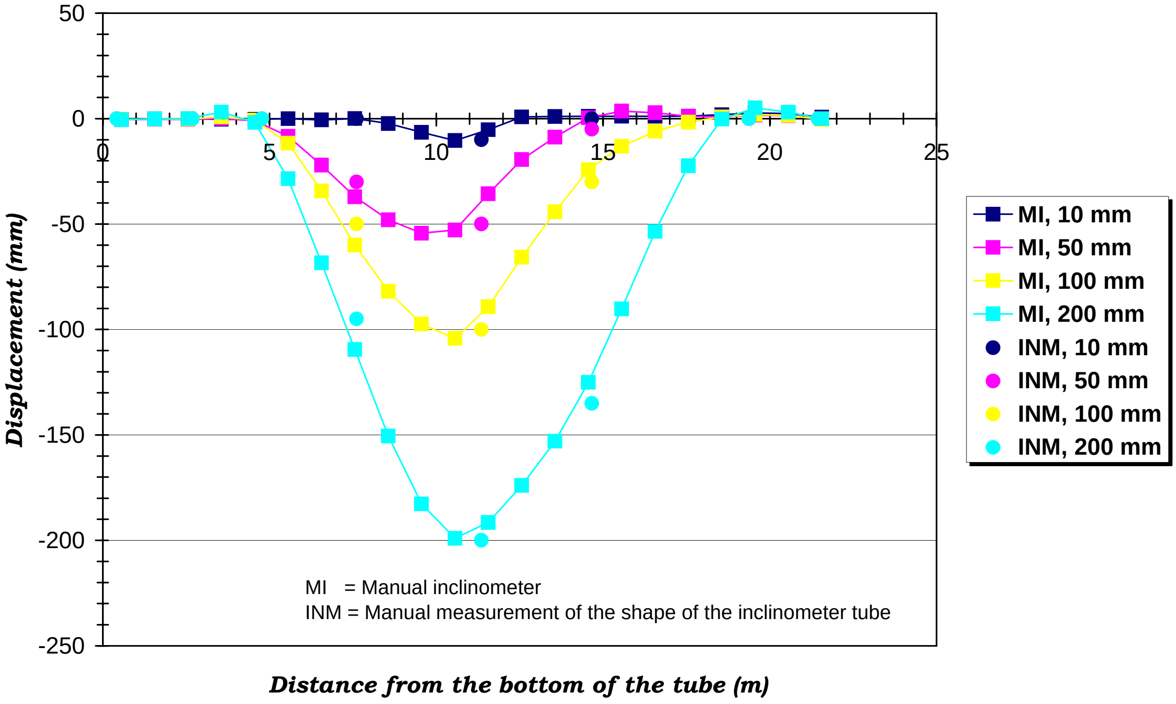


Figure ***5.20*** *Calculated horizontal displacements on the basis of measurements with the manual inclinometer for tube Shape-1. Manual measurements of the tube shape are plotted with filled circles.*

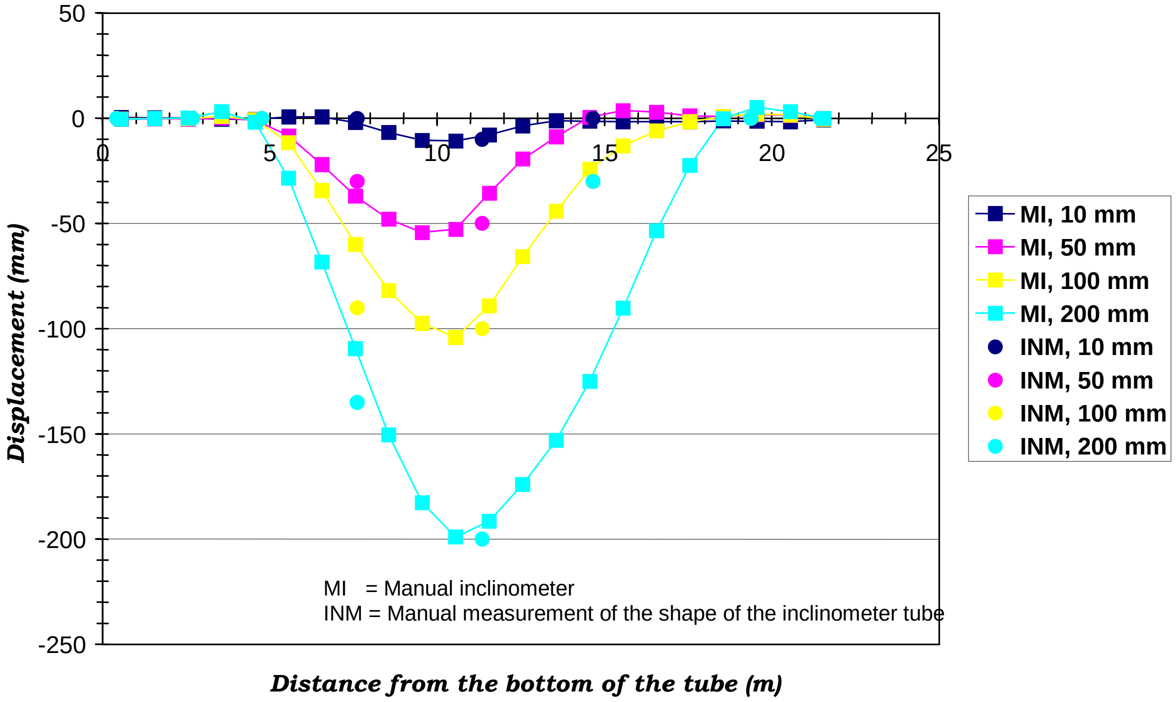


Figure ***5.21*** *Calculated horizontal displacements on the basis of measurements with the manual inclinometer for tube Shape-2. Manual measurements of the tube shape are plotted with filled circles.*

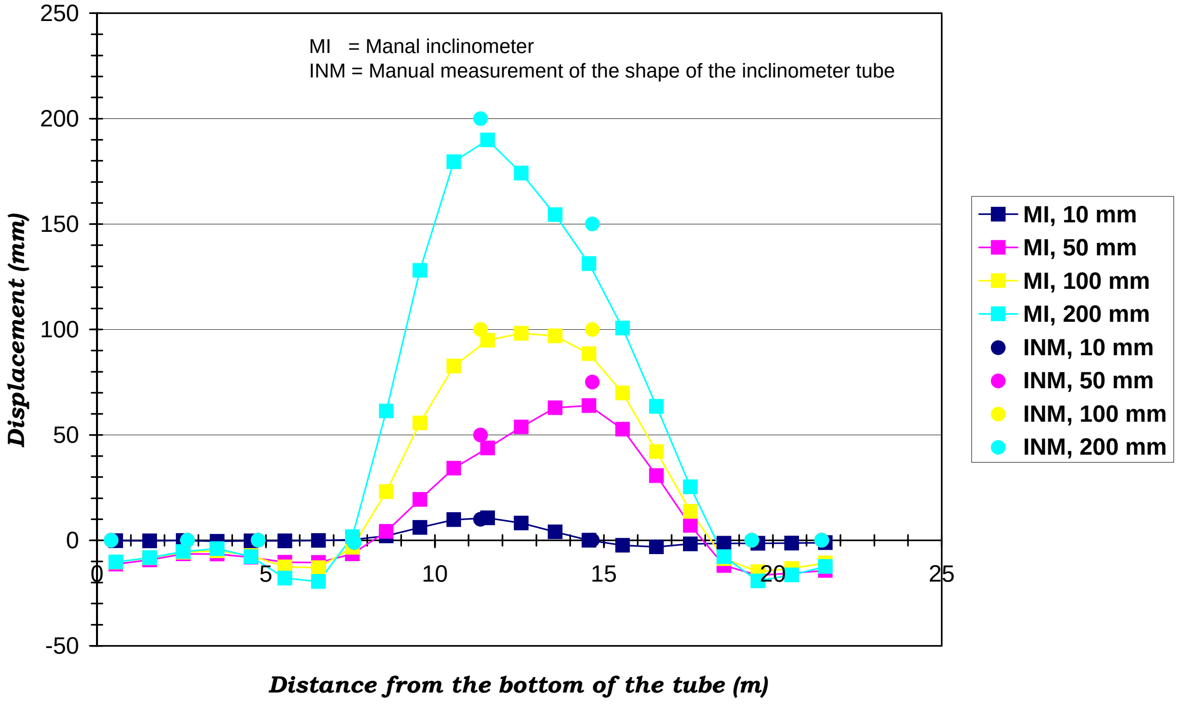


Figure ***5.22*** *Calculated horizontal displacements on the basis of measurements with the manual inclinometer for tube Shape-3. Manual measurements of the tube shape are plotted with filled circles.*

5.3.4.1 The automatic inclinometer

The standard procedure for installation and operation of the automatic system, as outlined in the introductory sections of this chapter, was followed during the tests.

Different tests with both the old type of connection between the distance rods and the inclinometer probes (slit and tube clamp) and the new type (pre-drilled holes and stop screw), as well as with and without joints between the probes and the rods were carried out. The full test program is shown in Table **5.8**.

Table ***5.8*** *Test program for automatic inclinometers in the vertical tube. Peripheral measurement means that the deviation of the probes with reference to the intended direction of installation was measured with reference to the ink lines drawn along the periphery of the inclinometer tube.*

Test No.	**Tube shape**	**Peripheral measurement**	**Screw connection**	**Joint**	**Deflection**
7	1	Yes	No	No	-
8	1	Yes	No	No	-
9	1	Yes	Yes	Yes	-
10	1	Yes	Yes	Yes	0
11	1	-	Yes	Yes	10
12	1	-	Yes	Yes	50
13	1	-	Yes	Yes	100
14	1	Yes	Yes	Yes	200
21	2	Yes	No	No	-
22	2	Yes	No	No	-
23	2	Yes	Yes	Yes	-
24	2	Yes	Yes	Yes	0
25	2	No	Yes	Yes	10
26	2	No	Yes	Yes	50
27	2	No	Yes	Yes	100
28	2	Yes	Yes	Yes	200
35	3	Yes	No	No	-
36	3	Yes	No	No	-
37	3	Yes	Yes	Yes	-
38	3	Yes	Yes	Yes	0
39	3	Yes	Yes	Yes	10
40	3	Yes	Yes	Yes	50
41	3	Yes	Yes	Yes	100
42	3	Yes	Yes	Yes	200
43	3B	Yes	Yes	Yes	0
44	3B	Yes	Yes	Yes	200
45	3B	Yes	Yes	Yes	100
46	3B	-	Yes	Yes	50
47	3B	-	Yes	Yes	10
48	1B	Yes	Yes	Yes	-
49*	1B	Yes	Yes	Yes	-
50*	1B	Yes	No	No	-
51	1B	Yes	No	No	-

The first test series with tube Shape-3 could not be completed as the measuring range of the inclinometer probes was exceeded. The tests were therefore repeated. In the result table these tests are marked with a 'B' after the tube number indicating the tube shape. Test No. 49 and 50 (denoted by *) were carried out with free hanging inner system for tube Shape-1. Duplicate ordinary tests were also carried out at the same time to be able to compare the test results, tests denoted by 1B as tube shape.

Measurements of the deviation from the intended direction of installation were first carried out for all of the inclinometer probes, Figures **5.23-5.25**.

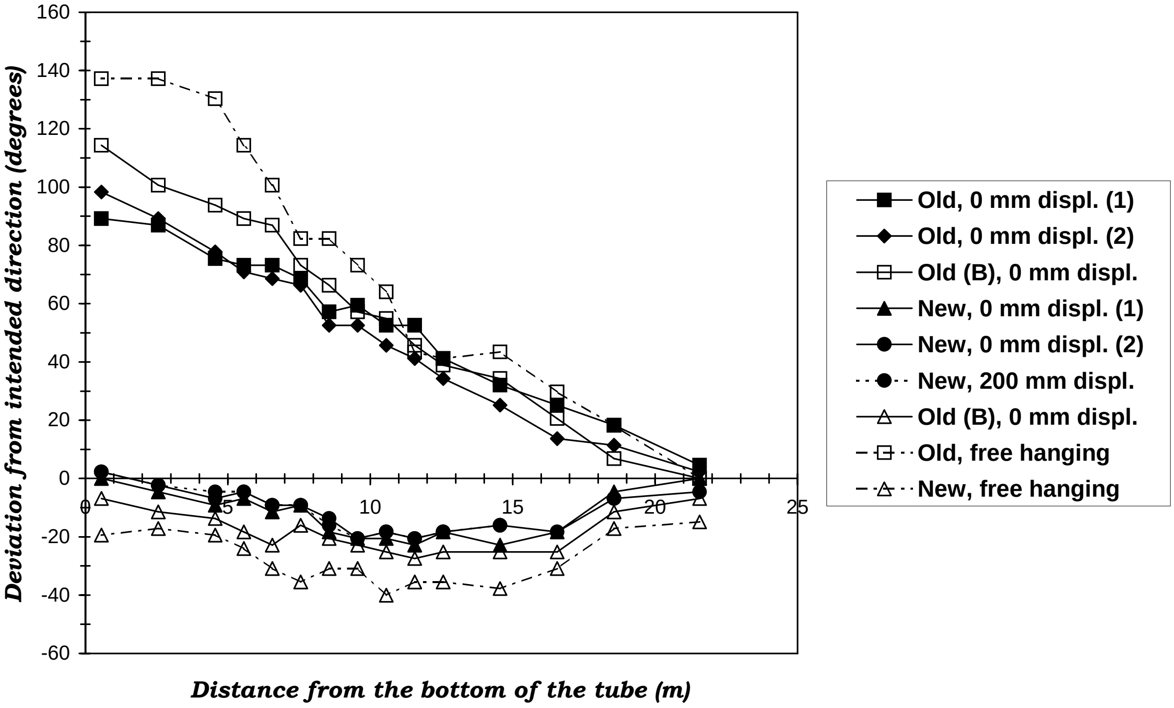


Figure ***5.23*** *Angular deviations with reference to intended directions of installation, tube Shape-1. "Old" refers to the old type of connection between the probe and the distance rod (slit and tube clamp), while "New" refers to the new type (pre-drilled hole and stop screw). "B" refers to a complementary test series, parallel with the tests on free-hanging inner system, in order to get comparative results. The numbers in brackets in the legend mark the order for repeated tests.*

The trends noticed from the horizontal tests are even more obvious and significant for the vertical tests when it comes to the angular deviation with reference to the intended direction of installation. For the old type of connection between the distance rods and the inclinometer probes (slit and tube clamp), the deviation increases, in principle, monotonously with installation depth. A maximum deviation of around 130° could be expected for the inner system with 15 probes used in the tests, in the worst case. The obtained result fits well into this prognosis. For the new type of connection (pre-drilled hole and stop screw) the angular deviations are considerably smaller and seem to occur somewhat arbitrarily in both directions around the intended direction of installation.

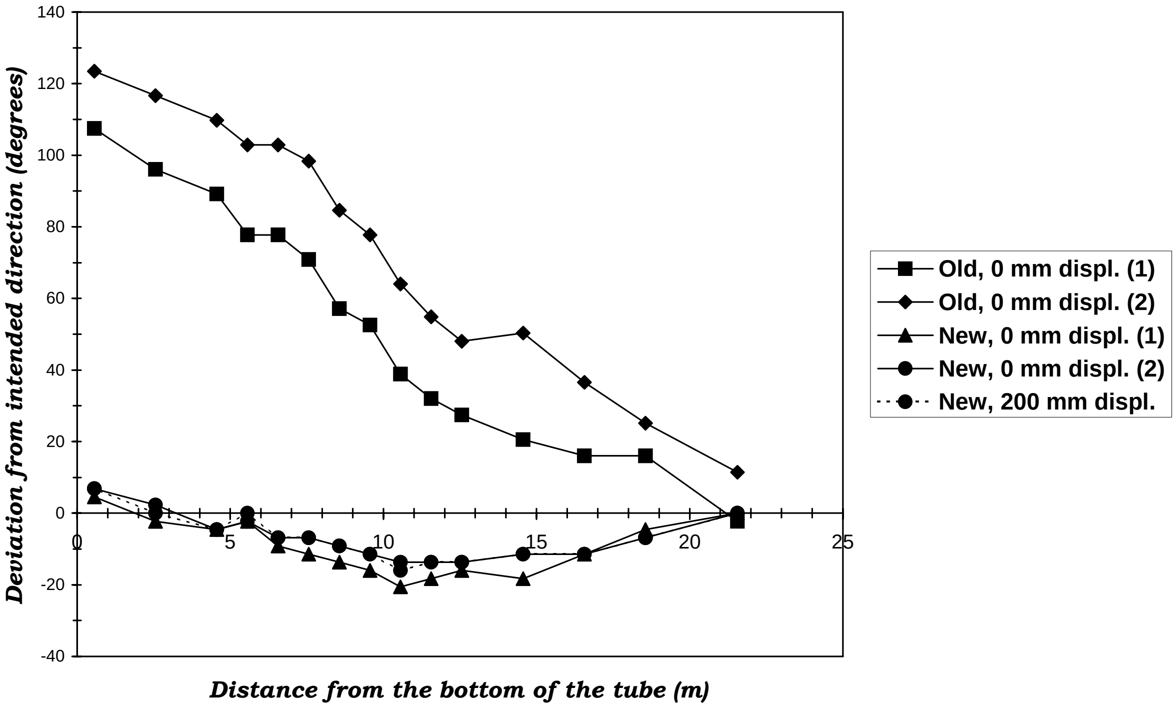


Figure ***5.24*** *Angular deviations with reference to intended directions of installation, tube Shape-2. "Old" refers to the old type of connection between the probe and the distance rod (slit and tube clamp), while "New" refers to the new type (pre-drilled hole and stop screw). The numbers in brackets in the legend mark the order for repeated tests.*

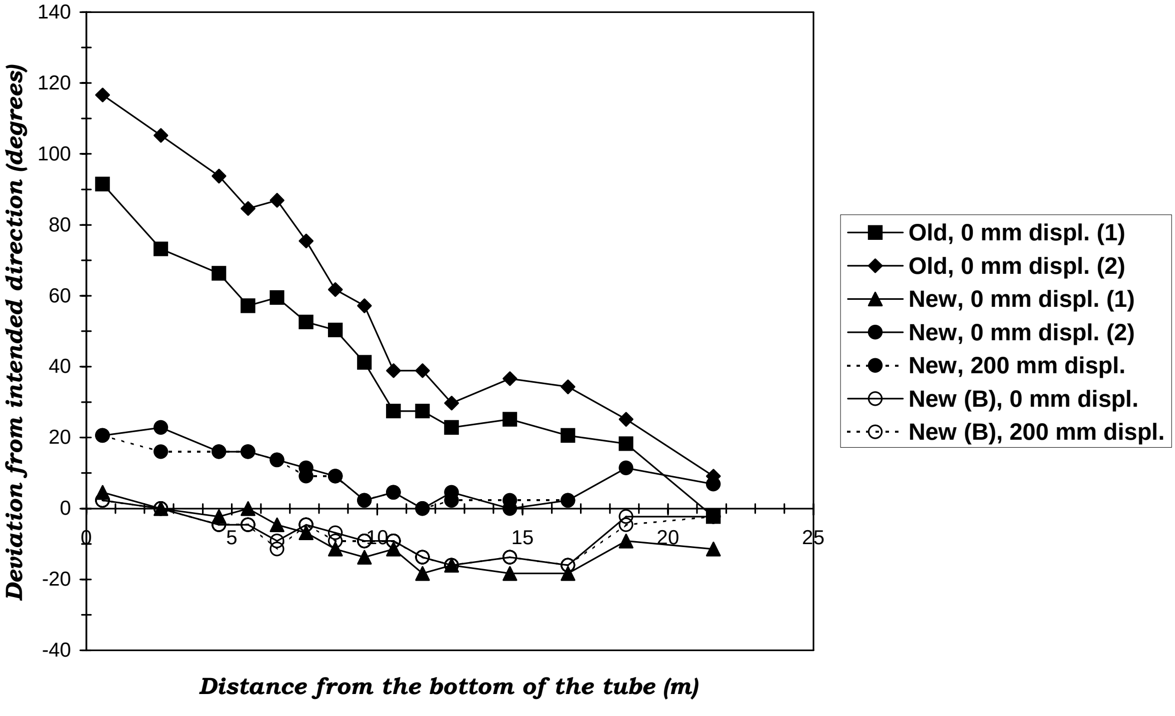


Figure ***5.25*** *Angular deviations with reference to intended directions of installation, tube Shape-3. "Old" refers to the old type of connection between the probe and the distance rod (slit and tube clamp, while "New" refers to the new type (pre-drilled hole and stop screw). "B" refers to a complementary test series, which had to be carried out as the range of the probes was exceeded in the first trial. The numbers in brackets in the legend mark the order for repeated tests*

Similar tests were carried out with the automatic system as with the manual system in order to investigate the capability of the inclinometer to capture a deflection of the inclinometer tube of known shape and magnitude. The results are shown in **Figures 5.26 – 5.28**.

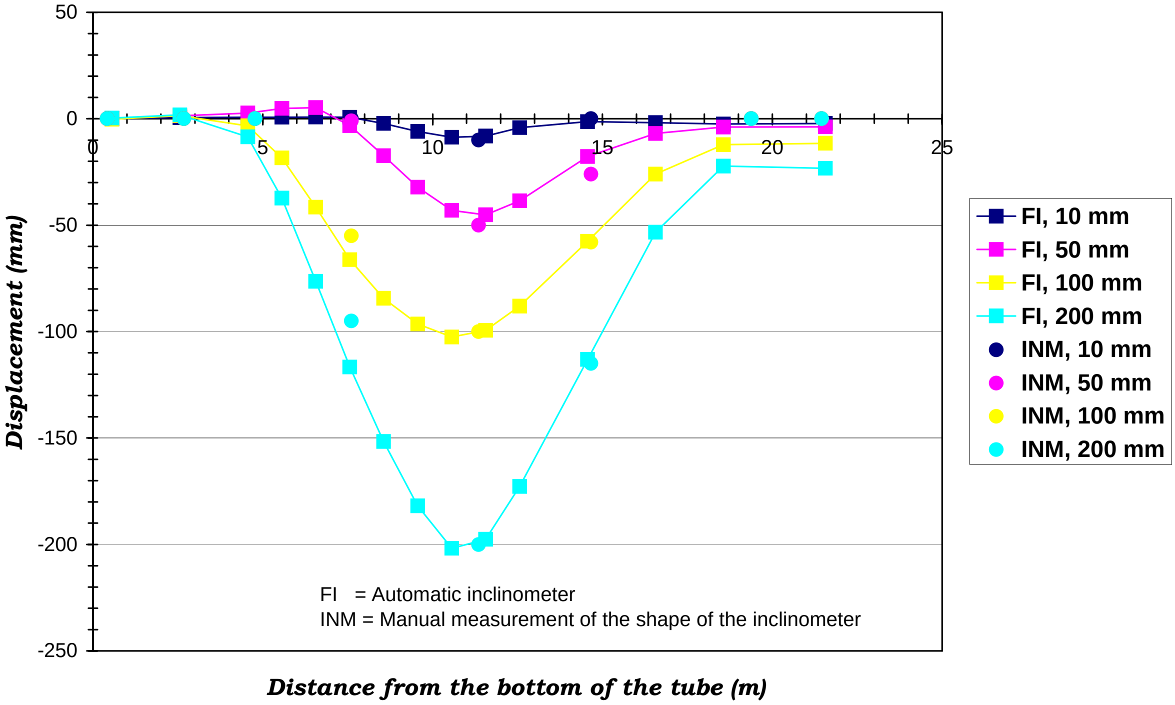


Figure ***5.26*** *Calculated horizontal displacement on the basis of measurements with the automatic inclinometer for tube Shape-1. Manual measurements of the tube shape are plotted with filled circles.*

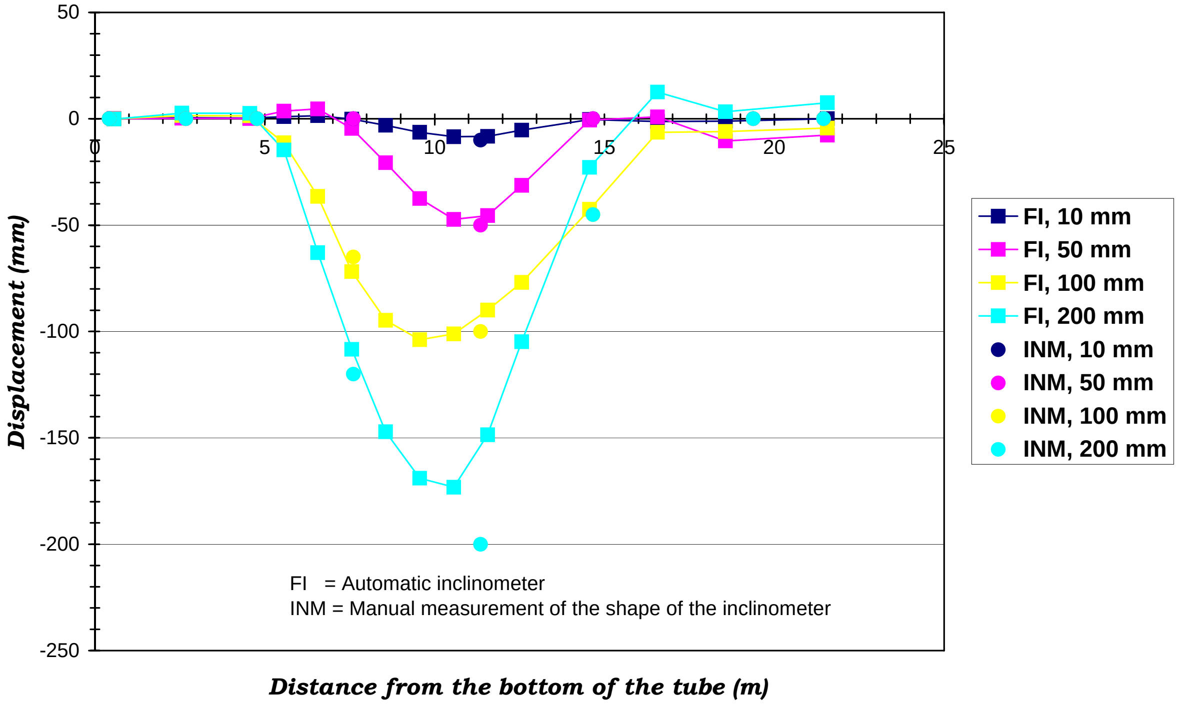


*Figure **5.27** Calculated horizontal displacements on the basis of measurements with the automatic inclinometer for tube Shape-2. Manual measurements of the tube shape are plotted with filled circles.*

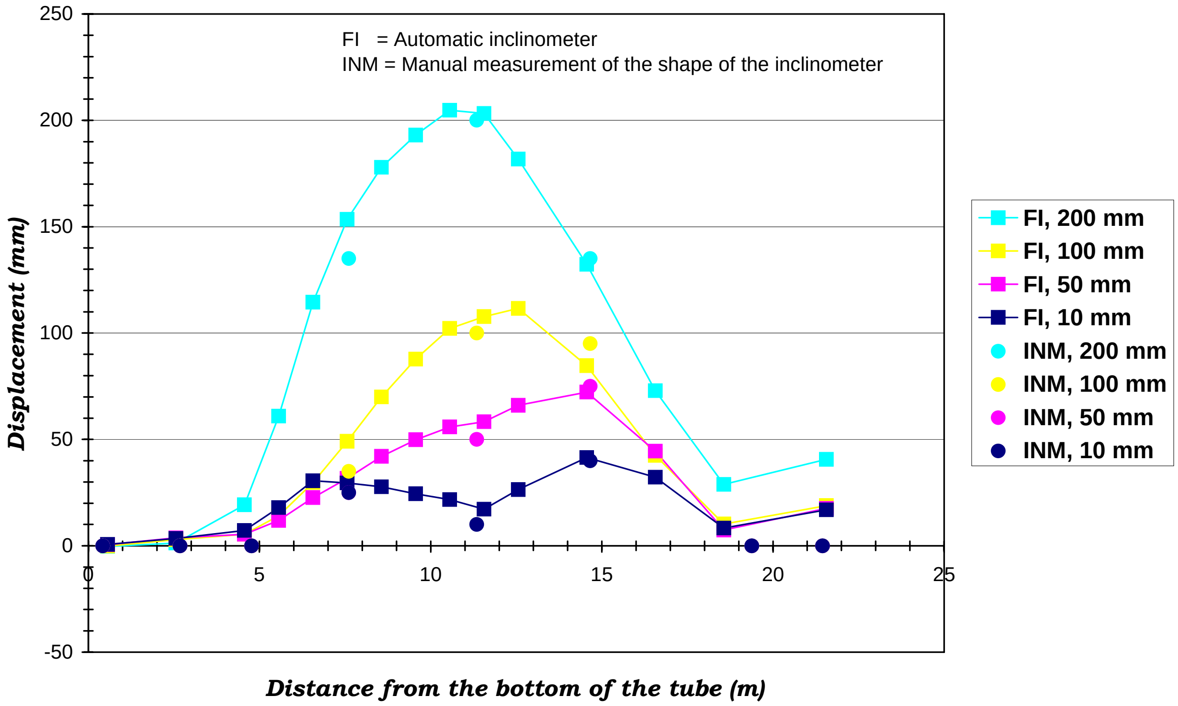


*Figure **5.28** Calculated horizontal displacements on the basis of measurements with the automatic inclinometer for tube Shape-3. Manual measurements of the tube shape are plotted with filled circles.*

According to the results in Figure **5.26 – 5.28**, the automatic system is well capable of capturing the known deflections of the inclinometer tube, even if the deviations from true values, as measured manually, in some cases are of larger magnitudes than for the manual inclinometer. The noticeable deviation for tube Shape-2 and a maximum deflection of 200 mm seems difficult to explain. Such a large discrepancy from the true value would not be expected, why malfunction in the measurement system might be suspected.

5.3.4.3 Conclusive remarks

The conclusive remarks for the vertical tests are divided into

- measured angular deviations after installation compared to intended directions of installation
- comparisons of captured deflections and known deflections.

Angular deviations

When it comes to the *manual inclinometer*, the angular deviations are small, in general, only up to maximum around 5° in these vertical tests, and probably of no practical significance. This result also implies that even if the aluminium rods do not show the torsion rigidity that would be desired, they still do show a satisfactory rigidity for practical use, at least for moderate lengths of the rod package.

For the *automatic inclinometer* system, the angular deviations depend mainly on the type of connection between the distance rods and the probes. The insufficient tolerance with the old type of connection (slit and tube clamp) leads to a monotonous increase in angular deviation with the number of distance rods/inclinometer probes used. With an inner system of maximum 15 probes, the deviation might be as much as around 130°, in the worst case. The inclinometer probe is then positioned away from the direction of measurement, i.e. the direction in which the maximum horizontal movements were expected to occur. Of course, with such a situation, the measurement data would be erroneous, or maybe more correctly expressed, the analysis and conclusions from the data would be erroneous. In some cases, it would be obvious that something is wrong, e.g. during the monitoring operation at the hospital in Lidköping where the movements were detected up slope, but in some cases it would probably not be as easy to reveal erroneous measurements. Many monitoring systems have been installed using this old type of connection, unfortunately also those, which serve as the basis for this Thesis.

On the other hand, the new type of connection, pre-drilled hole and stop screw, shows a much better performance. The angular deviations are smaller, as a maximum around 20°, but still not as small as for the manual system. They seem to be arbitrarily oriented, in the sense that they act somewhat randomly in both directions around the intended direction of measurement. The performance of the system became even better when the distance rods began to be manufactured at the Swedish Geotechnical Institute.

The normal question at this point would be to what extent deviations in the final direction of the inclinometer probe would influence the measurements. Well, with a deviation of over 50° and above, it is obvious that this is the case, as the inclinometer probe will be directed away from the direction of measurement, and no further analysis would be necessary. But what error would be introduced if the deviation would be, say 20 °, in general? By geometrical relations, it is possible to derive a correction factor, κ. If α is the deviation (°) between the intended and the actual direction of installation, the factor κ would be

$$\kappa = \frac{1}{\cos\alpha} \qquad \textbf{(5.11)}$$

The correct measurement value *M*, i.e. the inclination of the inclinometer probe, would then be

$$M_{correct} = \kappa \cdot M_{measured} \qquad \textbf{(5.12)}$$

And as cos α always is smaller than or equal to 1.0, the effect that the probe deviates from the intended direction of measurement would be that the values of the inclination that are registered are too small. The correction factor κ as function of the angular deviation from the intended direction of measurement is shown in Figure **5.29**.

From Figure **5.29**, it can be SEEN that with an angular deviation of say 30° the correction factor would be about κ = 1.15, I.E. an error of 15% would be introduced in the measurements of the inclinations with such a deviation.

The major problem though, if the measurement data are to be corrected in some way, is to determine the magnitude of the angular deviation. This deviation can, so Far, not be measured while the system is in operation, and can not either be determined with a high accuracy enough upon de-mounting. Besides, upon de-mounting, this information is probably of less importance as many important decisions regarding the management of the monitoring area, such as improvements of slopes with unsatisfactory stability conditions or even evacuation of areas, must be taken long before the inclinometer system is de-mounted.

In our somewhat perfect and ideal tests both the *manual* and the *automatic* inclinometer managed to capture the known deflection of the inclinometer tube in a satisfactory way. For the automatic systems, the differences in actual and measured deflections are a little larger than for the manual inclinometer. The tests in this study were carried out with the new type of connection (pre-drilled hole and stop screw), therefore angular deviations in the range of about 20° can be expected. According to Figure **5.29**, the error introduced in the measurements would be a maximum of about 6%. It should be noted though, that the deviation is not 20° for all inclinometer probes. For most probes, the angular deviation is considerably smaller, leading to a smaller error being introduced. The average error for the entire set of probes could most likely be expected to reach just a few per cent. This would probably not have any significant influence on the performance, and is probably the reason why we can not see any major difference between the ability of the manual and the automatic inclinometer to capture the known deflections of the inclinometer tubes in our tests.

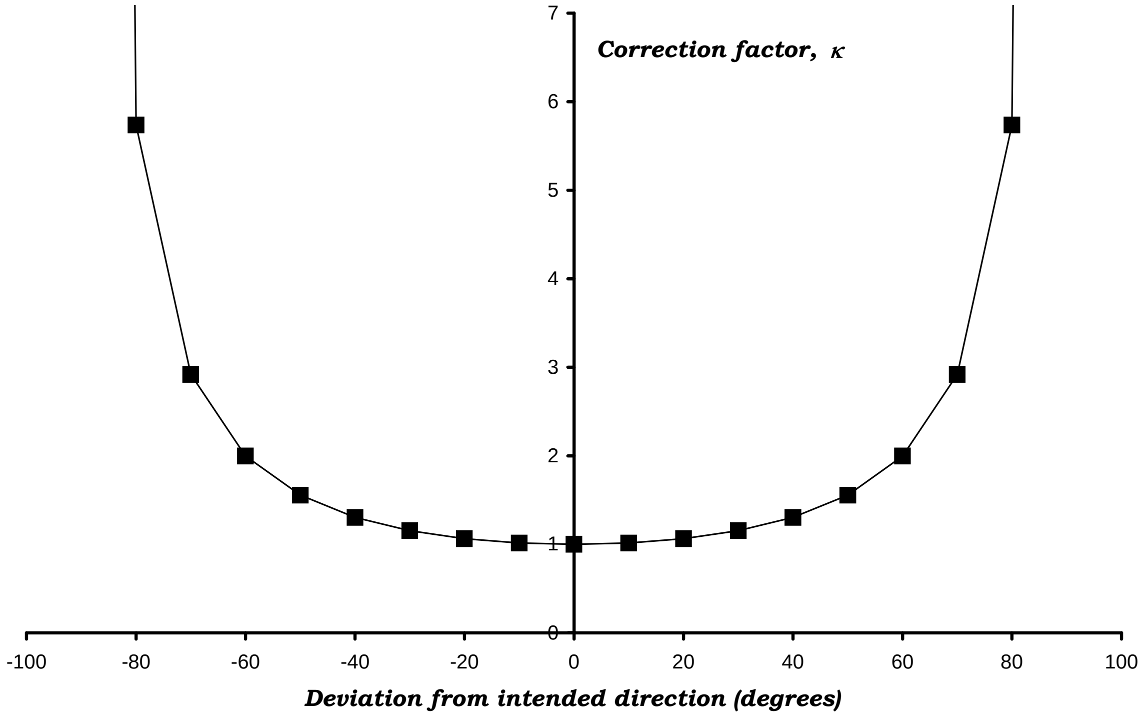


Figure ***5.29*** *Correction factor κ as a function of the deviation from the intended direction of installation/measurement.*

5.3.5 Integration scheme

The last aspect to investigate with inclinometer measurements is the influence of the integration scheme on the horizontal movements being calculated from the inclination measurements, or more correctly from the changes in inclination being measured. The changes in inclination are by means of some integration scheme, transformed to horizontal movements. This was all covered in the introductory sections of this chapter. Even if the integration procedure does not have much to do with the inclinometer measurements, as such, it plays an important role in the processing and analysis of the measurement data. Therefore, also this part is included in the study.

Significant for the two types of inclinometer system as they are operated and data are processed today, is that the integration scheme of the manual type is more sophisticated than the one used for the automatic system. The integration scheme itself is not in any way connected with the inclinometer system. Any scheme could, in principle, be used. As previously described, the scheme adopted for the manual inclinometer takes into consideration the measurement values at up to four adjacent levels. The effect of this is that the changes in movements are evened out and the shape of the inclinometer tube is modelled in a more realistic way. The automatic system, on the other hand assumes the value of the inclination to be constant between two probes, i.e. two measurement levels. The inclination values of the adjacent probes are not taken into consideration when integrating the values of inclination to horizontal movements. This kind of integration scheme is quite rough, especially considering the high technical level of the equipment. The integration scheme is schematically shown in Figure **5.30**.

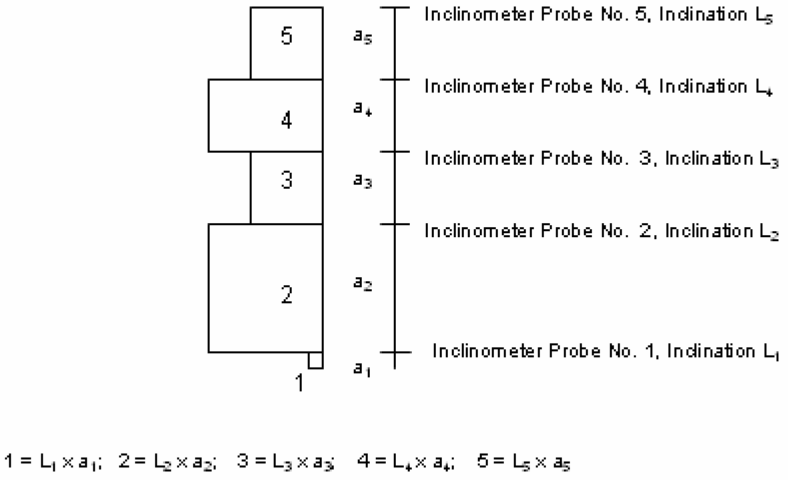


Figure ***5.30*** *Schematic picture of the integration scheme for the automatic inclinometer. The inclination is assumed constant between two probes and measurement levels, and the horizontal movement is simply assumed as the change in inclination multiplied with the distance to the closest probe below.*

Therefore, it is of interest to study the integration procedure a bit more in detail for the automatic system and what effect this somewhat simplified scheme actually has on the values of horizontal movement being calculated and presented.

First, however, the effect of the initial adaptation period, which, in fact, is more connected to the measurement method as such, must be handled in some way. All tests in this study indicate adaptation periods of up towards 30 days. In reality, this period can be even longer, and of course also shorter, all depending on the situation. In the beginning of this chapter, for example, the situation at Munkedal, Kviström Södra was described, compare Figure **5.7**, with an adaptation period of almost a year. As the slope was used as a "research slope", extensive measurements of different parameters were carried out, and also comparative measurements of horizontal movements with manual inclinometer. The conclusion is that no horizontal movements, corresponding to the measurement result from the automatic inclinometer system, occurred in the slope. The adaptation period, which can be observed in the measurement result, thus, is entirely caused by the automatic inclinometer system itself.

For shorter monitoring projects, where the total time of measurement most often is far shorter than the adaptation period, it would be quite difficult to know what is actually measured. There is probably no method of getting around this problem. Maybe, in the end, the best way would be to use the manual inclinometer for shorter assignments, at least if the expected magnitudes of the movements are small. The erroneous data from the adaptation period would, in most cases, be of larger magnitudes than the actual movements taking place in the soil. In such cases it would obviously be difficult to analyse and interpret trends in the measurement data.

For longer monitoring periods on the other hand, it would be possible to follow the trend in the rate of horizontal movements. After the adaptation period has come to an end, more reliable measurement data are obtained. The question then is how the assembly of measurements during and after the adaptation period should be handled in order to find the most likely magnitudes of horizontal movements.

One suggestion from the Inclinometer Evaluation Project is to evaluate linear segmental parts of the curves showing inclination as function of time. The first reliable segment is evaluated after the end of the adaptation period, and is extrapolated backwards to the beginning of the measurement period. The inclination value obtained in such a way would be used as the zero value, to which consecutive measurements should be related. The procedure is shown in **Figure 5.31**.

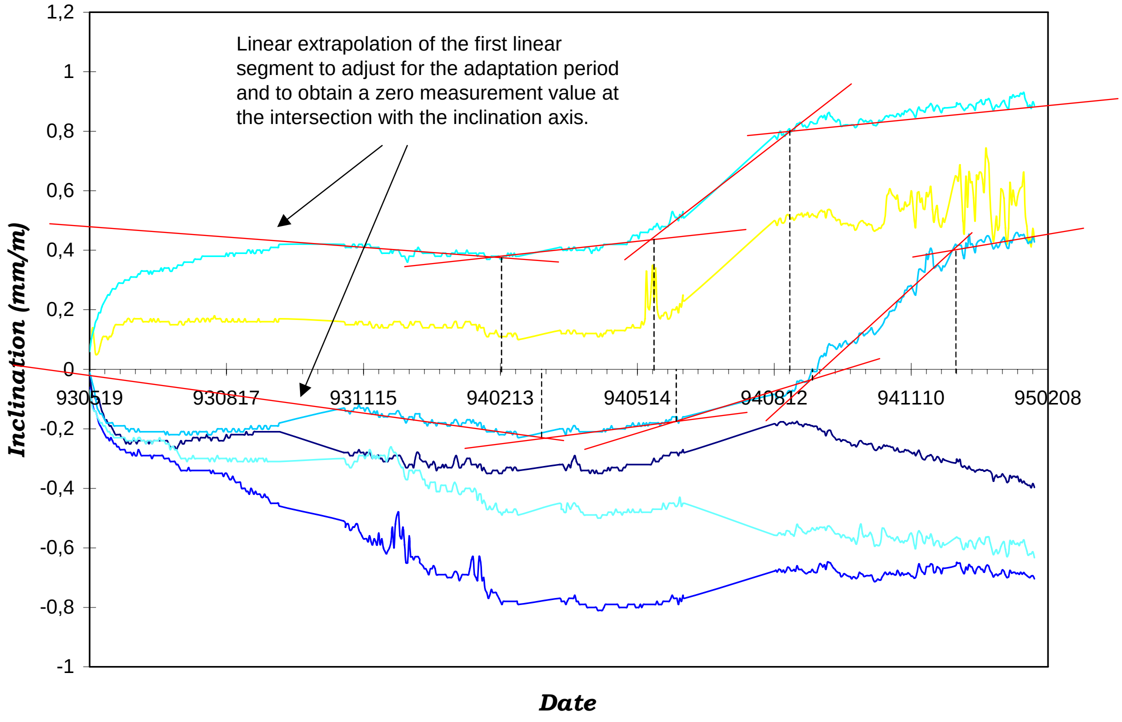


Figure ***5.31*** *Schematic view of the suggested method of handling the initial adaptation period using the automatic system. The original measurement curve is idealised with a number of linear segments. The first linear segment is extrapolated backwards over the adaptation period to obtain a zero measurement value at the intersection of the inclination axis (y-axis). Values of the inclination are read off for each breaking point between the linear segments.*

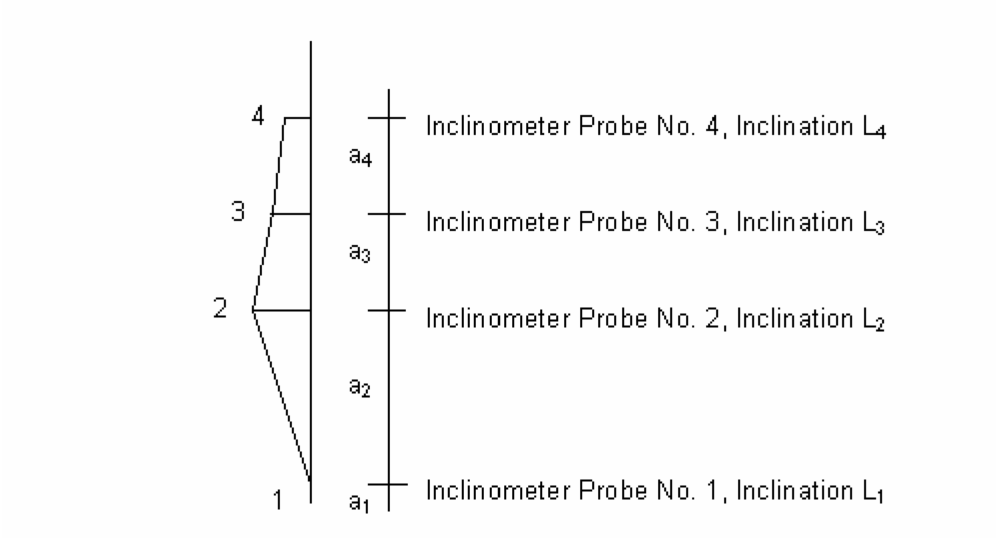
In Figure **5.31**, the zero value for the upper curve would be 0.48, and for the lower line it would be more or less 0.0. Consecutive measurements are reduced with these zero values to calculate the difference in inclination with time. The integration of changes in inclination to horizontal movements is then carried out according to the chosen integration scheme.

Another possibility to adjust for the adaptation period would be to move the point of time for the zero reading forward in time until the end of the adaptation period. The measurement values obtained at this point in time would then be the zero values, which all consecutive values should be reduced with. Applying such a method would however imply that information about movements occurring before the end of the adaptation period is lost. Therefore, a direct comparison with results using the manual inclinometer would also be difficult.

Once a method to overcome the undesired influence of the adaptation period is decided upon, a more refined integration scheme needs to be considered. There is no wish, at this time, to try to introduce a complicated scheme. The aim is to still use the same kind of simple approach, but to adjust it to better reflect the actual shape of the inclinometer tube.

The first reflection to be made is that the distance between individual inclinometer probes will have a considerable influence on the calculated horizontal movement. For the Research Slope in Munkedal, Kviström Södra, the distance between the lowermost inclinometer probes was 13 m. The horizontal movement at the level for probe *i*, according to equation (5.9), is calculated as the change in inclination measured by probe *i* multiplied by the distance to probe *i-1*. Assume now, for the sake of simplicity, that the change in inclination measured by probe *i* was 1 mm/m. With a distance of 13 m to the closest probe below, the adopted integration scheme would give rise to a calculated horizontal movement of 13 mm. Therefore, even a fairly small change in inclination would lead to quite a substantial horizontal movement, which of course, is not correct. One way to overcome this drawback would be to install more probes in the inclinometer tube, but this is not possible, as the maximum number allowed, because of the available space in the tube, is 15.

Furthermore, the deflection of the inclinometer tube does not occur in a block wise way, compare Figure **5.30**, which is assumed in the presently adopted integration scheme, but more in the shape of a smooth curve. One improvement to the integration scheme, but still very simple, would be to assume a linear variation of the change in inclination between the different measurement levels, i.e. the different probe levels, instead of constant values of the change in inclination used so far. The suggested adjustment is shown in Figure **5.32**.



$1 = L_1 \times a_1$; $2 = L_2 \times a_2/2$; $L_3 = L_3 \times a_3 + (L_2 - L_3) \times a_3/2$; $L_4 = L_4 \times a_4 + (L_3 - L_4) \times a_4/2$

Figure ***5.32*** *Schematic picture of the proposed adjustment to the integration scheme of the automatic inclinometer. A linear variation in the change of inclination is assumed between the different measurement levels, i.e. different inclinometer probes.*

All evaluations of automatic inclinometer measurements being used in this report follow the proposed improvements in this chapter.