In Situ Determination of Horizontal Ground Movements

Détermination in situ des mouvements horizontaux du sol

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Summary

The Swedish Geotechnical Institute has developed new inclinometers for accurate determination of horizontal ground movements. The instruments are normally applied in smooth flexible tubes installed vertically in the ground.

One purely mechanical device — the "SGI Rod Inclinometer" — is suitable for depths down to 4 metres. A second device — the "SGI Strain Gauge Inclinometer" — is used for depths down to 90 metres. This device has great accuracy due to the fact that the zero point travel of the strain gauges is eliminated through a special measuring method. Both devices also give the direction of the inclination of the flexible tube. The Strain Gauge Inclinometer permits polygon measurements starting from a firm bottom or any other bench mark. By repeated measurements, ground movements can be determined.

A third instrument — the "SGI Contact Pendulum" — consists of a pendulum in electrical contact with a remotely controlled micrometer screw. It can be left installed in the ground for a long time in order to check the changes in inclination at a given level, normally selected by previous measurements with the Strain Gauge Inclinometer. The Contact Pendulum may serve as a warning of excessive ground movements.

Sommaire

De nouveaux inclinomètres ont été mis au point à l'Institut Suédois de Géotechnique pour la mesure précise des mouvements horizontaux du sol. Ces appareils sont normalement placés dans des tubes lisses flexibles disposés verticalement dans le sol.

Un appareil purement mécanique — l'inclinomètre à tige SGI — est utilisable jusqu'à 4 m de profondeur.

Un autre appareil — l'inclinomètre à strain gages SGI — peut être employé jusqu'à 90 m de profondeur. Cet appareil est d'une grande précision, dûe notamment à ce que la dérive du zéro des strain gages est éliminée par la méthode de mesure adoptée.

Les deux appareils indiquent également la direction dans laquelle s'incline le tube flexible.

L'inclinomètre à strain gages permet de déterminer la déformée du tube flexible par des mesures en divers points, en partant de la base de ce tube si elle est fixe ou de tout autre repère. Des mesures répétées permettent de déterminer les mouvements du sol.

Un troisième appareil — le pendule à contact SGI — est constitué par un pendule qui entre en contact électrique avec une vis micrométrique commandée à distance. L'appareil peut être laissé longtemps dans le sol pour suivre les variations d'inclinaison à un niveau donné, choisi d'après les mesures faites antérieurement à l'aide de l'inclinomètre à strain gages. Le pendule à contact peut servir d'avertisseur pour déceler des mouvements du sol dépassant une certaine ampleur.

Introduction

Determination of horizontal ground movements is important in soil mechanics. In recent years many measurements of such movements have been taken all over the world.

The Swedish Geotechnical Institute in 1957 needed such measurements for a large-scale field test and for research into the kinetics leading to failure of natural slopes. The authors studied available borehole inclinometers for that purpose. Although a great variety of these are used for different purposes they could find no type which combined small diameter with high accuracy in the determination of size and horizontal direction of inclination. They therefore developed the special instruments described in the paper.

The SGI Rod Inclinometer

When, in June 1957, a large-scale consolidation test was started at Skå Edeby near Stockholm and measurement of horizontal displacements both at the ground surface and in the ground was considered essential, an available borehole inclinometer was used but failed to some extent. Another type was therefore urgently needed. Mr. A. Hallén, of the Institute's mechanical department, was put in charge of the development of a simple rod meter for shallow depths only, as it was probable that ground movements at great depths were small. This meter was soon in operation and has since been gradually improved.

Fig. 1 shows the measuring principle. A flexible tube with an internal diameter of 40-110 mm is installed in the ground and a straight rod is inserted in the tube with a flexible guide following the bends of the tube. Where the rod enters the tube it is centered by means of a disc and a spherical guide.

The inclination and length of rod between the guides determines the position of the centre of the lower guide in relation to the centre of the spherical guide. The position of the latter is determined by geodetic means in relation to a bench-mark.

The direction and the size of inclination are measured by means of an instrument mounted on the rod. The instrument has one part which can be fixed to the rod and one part which can be turned. The first part is fixed after the diopter has been directed in a chosen horizontal zero direction. Then the other part of the instrument is turned until a tangentially positioned spirit level indicates a horizontal position. That position corresponds to the inclination plane of the rod. The horizontal angle between this position and the zero direction is given by the position of an index on the turnable part in relation to a scale disc on the fixed part.

The inclination is obtained by setting a radial spirit level

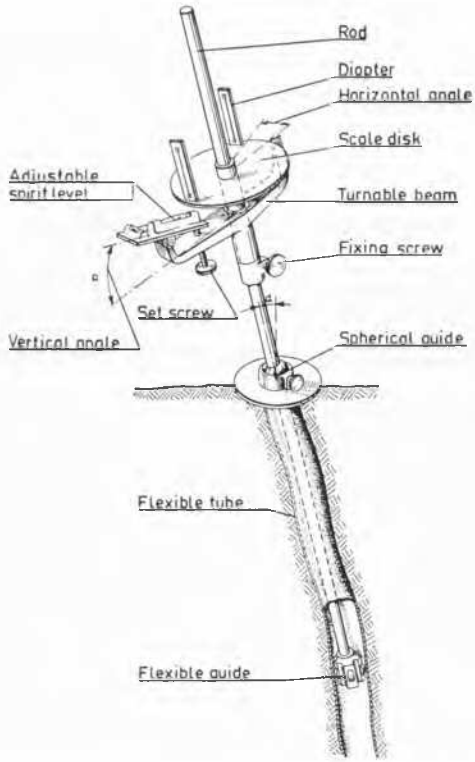

Fig. 1 Rod Inclinometer.
Inclinomètre à tige.

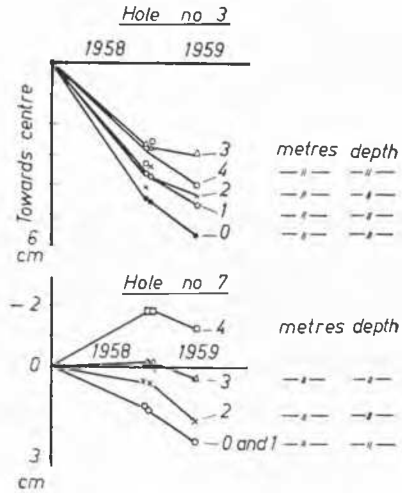

Fig. 2 Rod Inclinometer. Measurements at Skå-Edeby.
Inclinomètre à tige. Mesures faites à Skå-Edeby.

in a horizontal position by means of a set screw and reading the position either on the set screw, which in this case is a micrometer screw, or on a dial gauge (not shown in the figure).

To take a measurement the rod is inserted to different depths. For each depth three readings are taken, between each of which the rod is turned through 120 degrees. The observed scatter between these readings has averaged ± 0·35 mm deviation in horizontal direction for one metre's depth, ± 0·5 mm for two metres' depth and ± 0·9 mm for three metres'depth. At four metres' depth the scatter has hitherto increased suddenly about ten times to + 6·7 mm. The cause was an incorrect joint (as the rod had to be lengthened for that depth) but even the flexible guide can be influenced by the weight of the system (which probably also is the reason why the relatively minimum scatter was obtained for two metres' depth). These parts have now been improved.

Fig. 2 shows some measurements made over a period of two years at Skå Edeby.

The Rod Inclinometer seems to be particularly suitable for measurements on embankments and levees for depths down to 4 metres. Its main advantage is its simplicity.

The SGI-Strain-Gauge Inclinometer

The Strain-Gauge Inclinometer was primarily intended for the determination of horizontal movements in clay down to 20-30 m depths but has also been used with piles (70 m length) and for measurements in an earth dam which will have a height of 90 m when completed.

For measurements in clay a flexible tube with an inside diameter of 40 mm is installed vertically in the ground. If possible the lower end of the tube is fastened to firm bottom. That point can then provide a bench-mark for measurement of the horizontal travel of the tube. In addition the position of the upper end of the tube should, when possible, be determined on the surface. By combining a fixed lower end and a measured upper end the accuracy can be checked. Even if the positions of the ends are neglected useful information about relative soil movements is obtained from the shape of the curves.

The instrument, in its cylindrical cover, is directed by means of a spring and guiding knobs within the plastic tube. Each end of the cover is in contact with the tube wall at three points, and the axial distance between the contact points is 200 mm.

When measuring the inclination and the horizontal direction of the plastic tube at different levels the shape of the tube can be determined as a polygon. The conformity of the computed polygon to the tube centre line is dependent on the spacing of the measuring levels and on the curvature of the tube. For a tube with a continually gentle slope this spacing can be increased, whereas a tube with inflexion points will need closer spacing. The necessary spacing is also determined by the stiffness of the tube. A stiff tube is less sensitive to local changes and permits greater spacing while a softer tube follows the ground movements more closely and requires more measuring points.

In practice the authors usually carry out the first two series of measurements with a spacing of 0·5 m; thereafter the suitable spacing is prescribed for each tube (even with regard to economy).

The measuring principle of the inclinometer should permit determination with high accuracy of even large angles in tubes of 40 mm inside diameter.

The chosen method is based on the measurement (by electrical resistance strain gauges) of the strain in a leaf spring stressed by a weight (Fig. 3). The usually disturbing factors with strain gauge measurements (e.g. zero drift, creep, varying temperature differences between the measuring bridge and the inclinometer in the ground) do not influence the measuring result owing to the adoption of the measuring procedure that the meter is turned round in the tube. During one turn the spring will first deflect in one direction until, after a maximum deviation value (Fig. 4a) (which is indicated as a strain value at the measuring bridge), it then deflects in the opposite direction to another maximum (Fig. 4b) giving another strain value. It is the difference between these values which is calibrated against a known inclination of the instrument.

In practice the inclinometer is inserted into the plastic tube to the desired level by means of extension tubes (normally

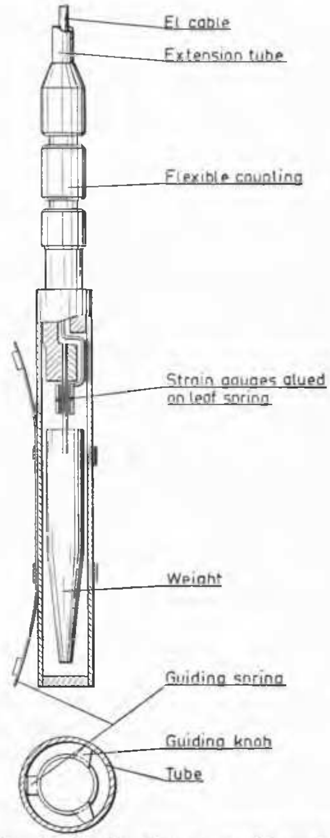

Fig. 3 Strain Gauge Inclinometer.
Inclinomètre à gages.

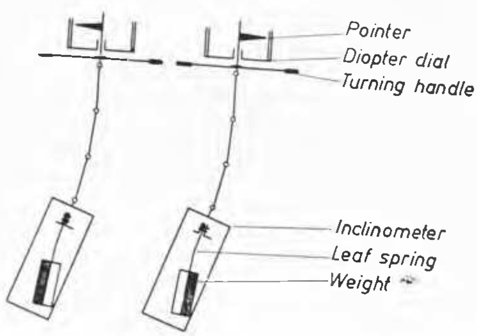

Fig. 4 Strain Gauge Inclinometer. Measuring Principle.
Inclinomètre à gages. Principe de mesure.

one metre in length) provided with flexible couplings (Fig. 5). After that a turning handle is fastened to the uppermost extension tube. The whole system is then rotated for measurement.

The direction of the plastic tube in horizontal projection at the actual level is determined by means of a diopter dial fixed in a certain position on the extension tube. All screws on the couplings and on the extension tubes are positioned along a straight line and hence the pointer of the diopter dial (Fig. 4) indicates the horizontal direction of the inclinometer when it has reached one of the positions of maximum deflection (which can be obtained from the bridge reading if the electrical cables are connected to the bridge in suitable order). The angle of horizontal direction is then read on the dial between the pointer and a line to an arbitrary chosen fixed point on the surface. The measuring accuracy of the inclinometer is dependent on the stability and freedom from

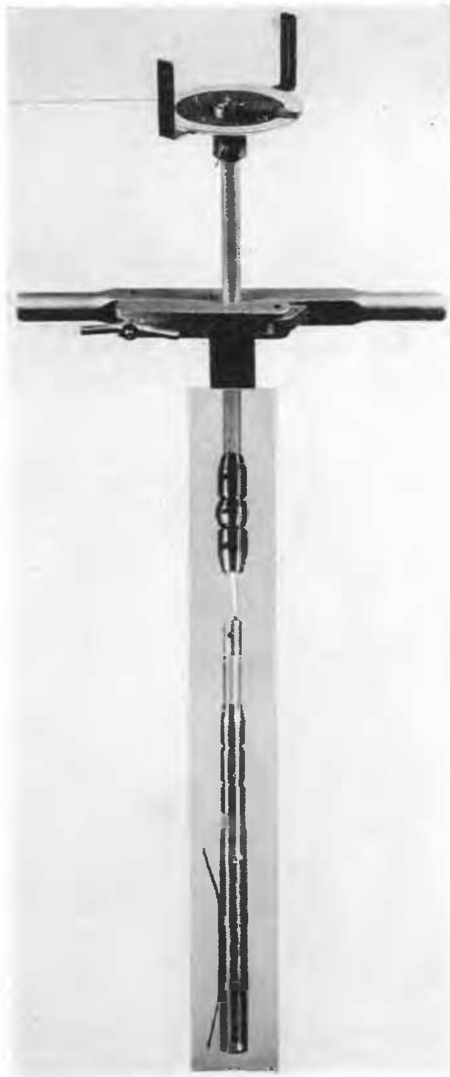

Fig. 5 Strain Gauge Inclinometer. Measuring Set Up.
Inclinomètre à gages. Equipement de mesure.

hysteresis of the leaf spring. If the allowable stress on the spring is too limited, the resistance variations in the strain gauges may be too small for a safe indication on the bridge. How personal factors may influence accuracy, especially when compensating and reading the bridge, was examined by comparative tests. Three measurements in a tube at Skå Edeby were carried out by three different staffs. The tube happened to lie in a plane and the obtained horizontal coordinates in this plane are shown in Table 1.

Table 1

Depth m	*Coordinate* 1st measurement mm	2nd measurement mm	3rd measurement mm
0	0	0	0
1·50	74	73	73
3·00	157	156	155
4·50	253	251	252
6·00	353	354	354
7·50	468	469	469
9·00	—	597	597

These and later field measurements by the authors have shown that the Strain-Gauge Inclinometer now has an accuracy better than $\pm$ 0·02° for inclinations below 45°.

The results of the measurements are presented in a three-dimensional coordinate system either by setting up graphically the curve of the tube, or by computing its coordinates, which is more accurate. Fig. 6 shows the results of two measurements where a certain change has occurred in the meantime. Such a method of presentation is correct but hardly examinable. When the first aim of the investigations is to determine horizontal movements it is often sufficient to establish the principal plane of movement and to report the results only in this plane in a manner that the variations against the initial position of the tube are shown. Comparison of results is furthermore facilitated when measurements are always made at the same depths.

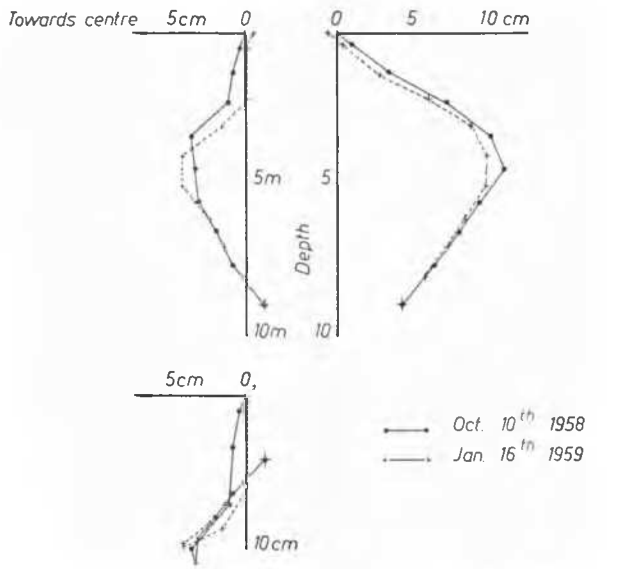

Fig. 6 Measurements at Skå-Edeby (Strain Gauge Inclinometer).
Mesures faites à Skå-Edeby (Inclinomètre à gages).

In Fig. 7 the results of measurements in a slope at the Göta River Valley are set out. The slope runs out in a tongue-like shape, and the principal plane of movement coincides with the axis of the tongue. The plastic-tube was set down through a clay stratum to a bottom layer of moraine where its conical iron tip was fixed at a depth of 17·25 metres. The position of the upper end of the tube is determined against a bench-mark in the vicinity. Thus the position of the tube, determined from the fixed tip, can be checked on the surface. The first series of measurements is represented by the vertical axis, and the deviation from these initial values is indicated in the diagram. The curves reveal that lateral displacements in the soil obviously begin at a depth of about 8 m. Moreover an increasing tendency of the curves to buckle is visible. This is due to (observed) vertical settlements. When the soil settles it presses down the tube by friction thus causing small lateral deflections. By coating the tube with asphalt protected by a bandage of aluminium strips, friction between soil and tube can be reduced. Such an arrangement has been made at Skå Edeby, but for the present measurements it was considered unecessary and uneconomical. So far this simplification seems to have been acceptable.

The method of controlling the position of a vertically installed plastic tube in the ground by the Strain-Gauge Inclinometer is now used for observation purposes at different sites. For a bridge abutment extensive excavations and considerable piling work had to be carried out, and harmful movements

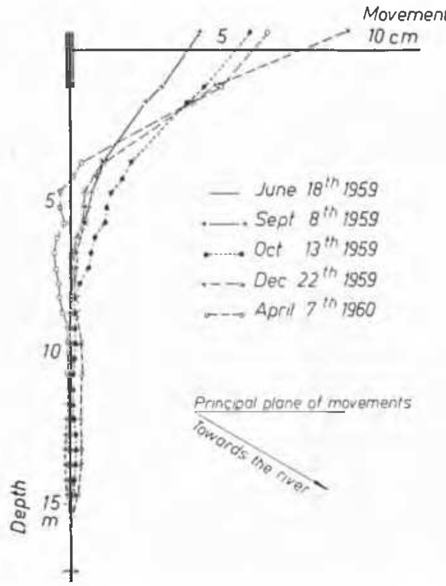

Fig. 7 Measurements at Strandbacken (Strain Gauge Inclinometer).
Mesures faites à Strandbacken (Inclinomètre à gages).

were feared. Hence two plastic tubes were installed from sea level in front of the abutment area. Both excavation and piling were reflected in the movements of the tubes. After piling the movement ceased.

Another problem has appeared in a large earth dam, where the lateral variations in a set of vertical telescopic tubes had to be determined. When completed, the dam will have a height of 90 m. The loosely jointed telescopic set (tube diameters 40 mm and 53 mm) is in the first place intended for the determination of settlements. For the purpose of measuring the change in inclination the guiding cover of the inclinometer had to be constructed in such a way as to give reliable contact of the instrument for tubes of varying diameter.

For the determination of the curvature of piles the strain-gauge inclinometer has been applied to reinforced concrete piles of 70 m length. The tubes for the inclinometer were set along the axis of the piles.

The SGI Contact Pendulum

In the Göta River Valley in southwestern Sweden slides occur frequently and it was desired to install instruments in the ground to warn against possible slides earlier than occasional observation of the ground surface can do.

The authors designed an instrument which could be left in the ground for a long time and could be operated by a non-specialist.

The chosen procedure was to install a tube as for the Strain-Gauge Inclinometer. A few consecutive measurements were then made with the Strain-Gauge Inclinometer to get a general idea as to where movements occur in the ground. Finally a long-term inclinometer is installed at the actual depth and with a horizontal orientation determined by means of the Strain-Gauge Inclinometer or otherwise.

The Contact Pendulum has been developed for such long-term purposes. In principle it is a mechanical device as shown in Fig. 8. The pendulum is hinged on ball-bearings and assumes a vertical position. A micrometer-screw can be turned by means of a thin shaft and a gear. When the screw touches an electrical contact on the pendulum, a signal is obtained above ground. The pendulum and contact are immersed in oil which provides protection against corrosion and has a damping effect on the pendulum.

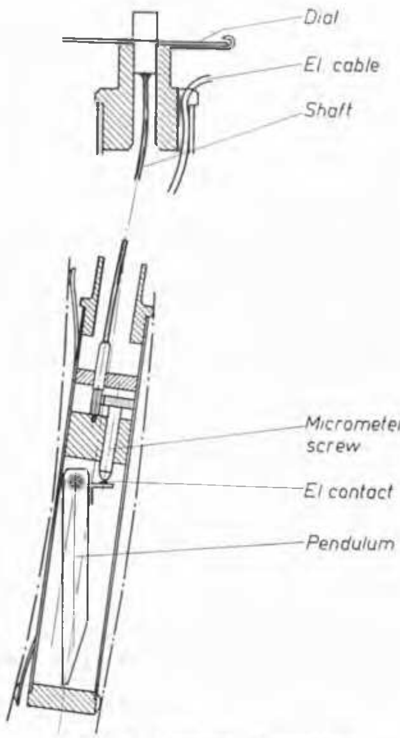

Fig. 8 Contact Pendulum.
Pendule à contact.

This damping ensures good electrical contact without noticeable deflexion of the pendulum. Care is taken to use a very weak current and never to break the contact with the current switched on. Thus great accuracy (contact travel about 1 μ) and long life of the contact is ensured.

The mircrometer screw is manipulated from above ground by means of a turning knob (provided with a dial). A 90° turn of the dial means a 0·1° corresponding change in inclination of the pendulum. Therefore the twist of the shaft — which is only a few degrees — does not influence the results.

By counting the necessary number of rotations of the dial to get a contact and comparing that number with the number of turns required when the instrument is held in a vertical position the inclination can be determined. This is, however, not the recommended procedure when checking ground movements. In such cases it is sufficient to install the Contact Pendulum in the tube and turn the dial until contact is obtained. This gives an initial position. Then the dial is turned backwards. After some time a new contact is established and the change in inclination is obtained from the difference of the readings.

A possibility (not yet applied but intended to be performed) is the application of an arrangement giving an automatic signal. One can then open the contact gap a known distance. When the inclination reaches a corresponding value a signal is obtained. If the soil in a slope is creeping at a certain rate the contact can be preset to cover the movement during a certain period of time. If the movement is accelerated a signal is obtained before the presumed time interval is ended.

Two types of contact pendulum have been made. One specimen of the ordinary type had been left in the ground for eighteen months up to the time of writing. At Skå Edeby this meter was installed 2 metres apart from a tube where measurements were performed with the Rod Inclinometer. Fig. 9 shows a comparison of the measurements. The contact pendulum has remained sensitive.

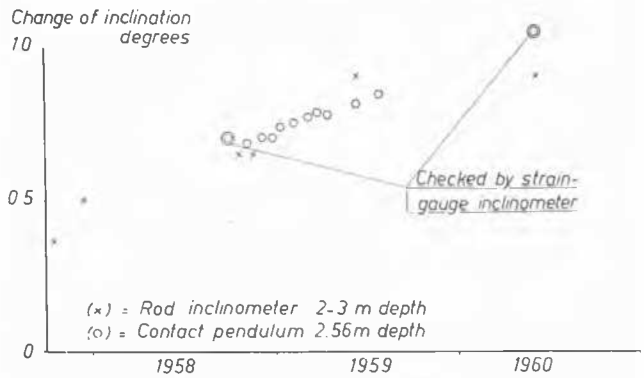

Fig. 9 Measurements at Skå-Edeby (Rod Inclinometer, Contact Pendulum).
Mesures faites à Skå-Edeby (Inclinomètre à tige et pendule à contact).

A precision pendulum has also been built with a sensitivity of about 0·002° (measuring range 0-1°). This indicates that the principle can give a high degree of accuracy.