Italian Motorway System: Experiences with In Situ Tests and Inclinometer Surveys for Urgent Remedial Works

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This paper deals with the philosophy adopted by the company Autostrade SpA for the maintenance of a motorway network about 2700 km long. A case study of a slope failure is presented to illustrate the application of this philosophy. In particular, a possible misjudgment in the design of remedial works performed only on the basis of quick in situ tests is reported. Because of the importance of inclinometer surveys in dealing with slope failures, some useful observations about processing criteria for inclinometer data are presented. The procedures adopted to avoid or, when possible, to overcome instrumentation errors are also discussed.

Since the opening of the first multilane motorways in the 1960s, routine landslide monitoring has consisted almost entirely of on-site inspections by maintenance personnel. In cases that appeared particularly severe, geotechnical investigations that involved the installation of monitoring devices were performed as well.

The design of the remedial measures can be divided into the following typical stages:

1. Retrieval of all the available information, such as the original design, technical reports, investigation data, and accounts of the construction works (measurement logbooks).
2. Drafting of a preliminary study that includes the following items: (a) geological and geomorphological analysis (e.g., photointerpretation, in situ survey) leading to a comprehensive definition of the slide area; (b) stratigraphic and geotechnical characterization of the soils involved in the slide; (c) indication of the first measures to be undertaken; and (d) a program of in situ and laboratory tests and/or a monitoring system.
3. Execution of the in situ and laboratory tests and reading of the monitoring instruments.
4. Final design of the remedial measures.

Unless comprehensive data are already available, the average time required to go from Stage 1 through Stage 4, after a slide has been reported, is of the order of 8 to 12 months, which can be broken down as follows:

- One to two months to acquire the necessary data and draw up the preliminary study;
- Two to three months to perform the soil investigation;
- Three to five months to carry out the laboratory tests and to obtain significant data from the monitoring system;
- Two months for the final design of the remedial measures.

The progression of the mass movement usually "respects" the time required for investigations and design. In some cases, however, slides may undergo sharp acceleration and seriously interfere with normal traffic, thus calling for emergency actions. In such cases, "on-the-spot" decisions regarding measures to be adopted may result in extremely difficult and unreliable designs unless specific data are readily available. According to the authors' experience, these specific data must consist of:

- The results of quick in situ tests, such as cone penetration tests (CPTs), standard penetration tests (SPTs), dilatometer tests (DMTs), and stratigraphic boreholes.
- A technical and historical data bank relevant to the region that includes the area under consideration (*1*). The data bank should contain the characteristics of a significant number of registered landslides, including: (a) the type of failure, e.g., according to the classification presented by Varnes (*2*); (b) the volume of soil involved; and (c) indications that allow designers to know whether the slip surfaces usually develop along particular stratigraphic interfaces recurring in the region.
- Geotechnical parameters of the soil involved and/or correlations that are specific for the region considered. For example, using the results of laboratory tests conducted on more than 150 samples relevant to 20 sites along the "Autostrade SpA" network, a correlation linking residual friction angle, gradation, and index properties of cohesive soils was found (Figure 1). The correlation is very useful as a guide in the urgent design of remedial works when the data from an extensive laboratory program is not readily available.

Without an adequate data bank, the analysis, based only on quick in situ tests, may be unreliable. The following example shows, for a specific landslide, a possible misjudgment in the selection of an "urgent" design based on the analysis of the few data available instead of the complete data listed in Stages 1 through 4.

The landslide under consideration is situated along the Naples-Bari motorway (A16) in the southern Apennines region. The landslide area, 400 m long and about 70 m wide, was defined by means of geomorphological analysis (photo-

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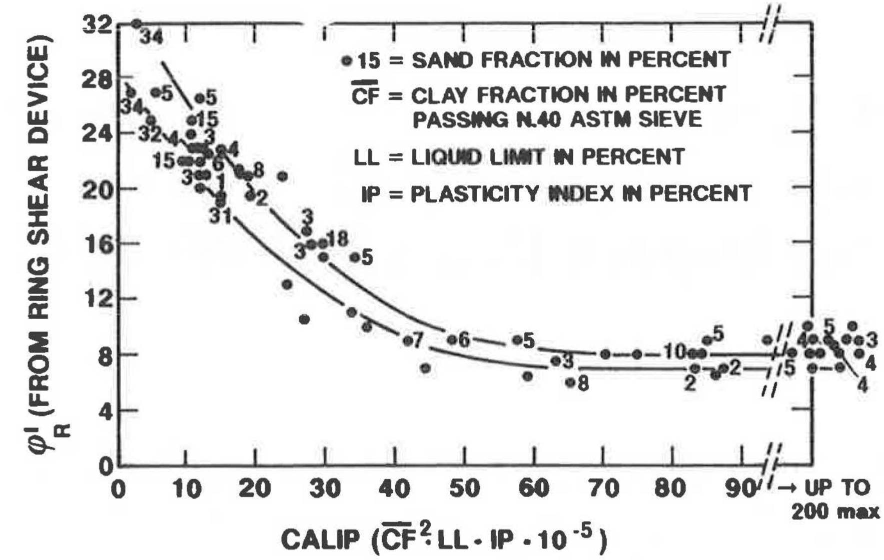

FIGURE 1 Correlation between residual friction angle, gradation, and index properties of cohesive soils.

interpretation and in situ survey) and is shown in Figure 2. A geotechnical investigation was performed in this area to a maximum depth of 35 m from ground level. The investigation consisted of

- Five geotechnical boreholes, four of which were instrumented with inclinometric tubes. In each borehole, several SPT tests were conducted and undisturbed samples were obtained.
- Four boreholes instrumented with Casagrande piezometers (two cells in each borehole).
- Ten continuous dynamic penetrometer tests.

The location of this investigation is shown in Figure 2. The

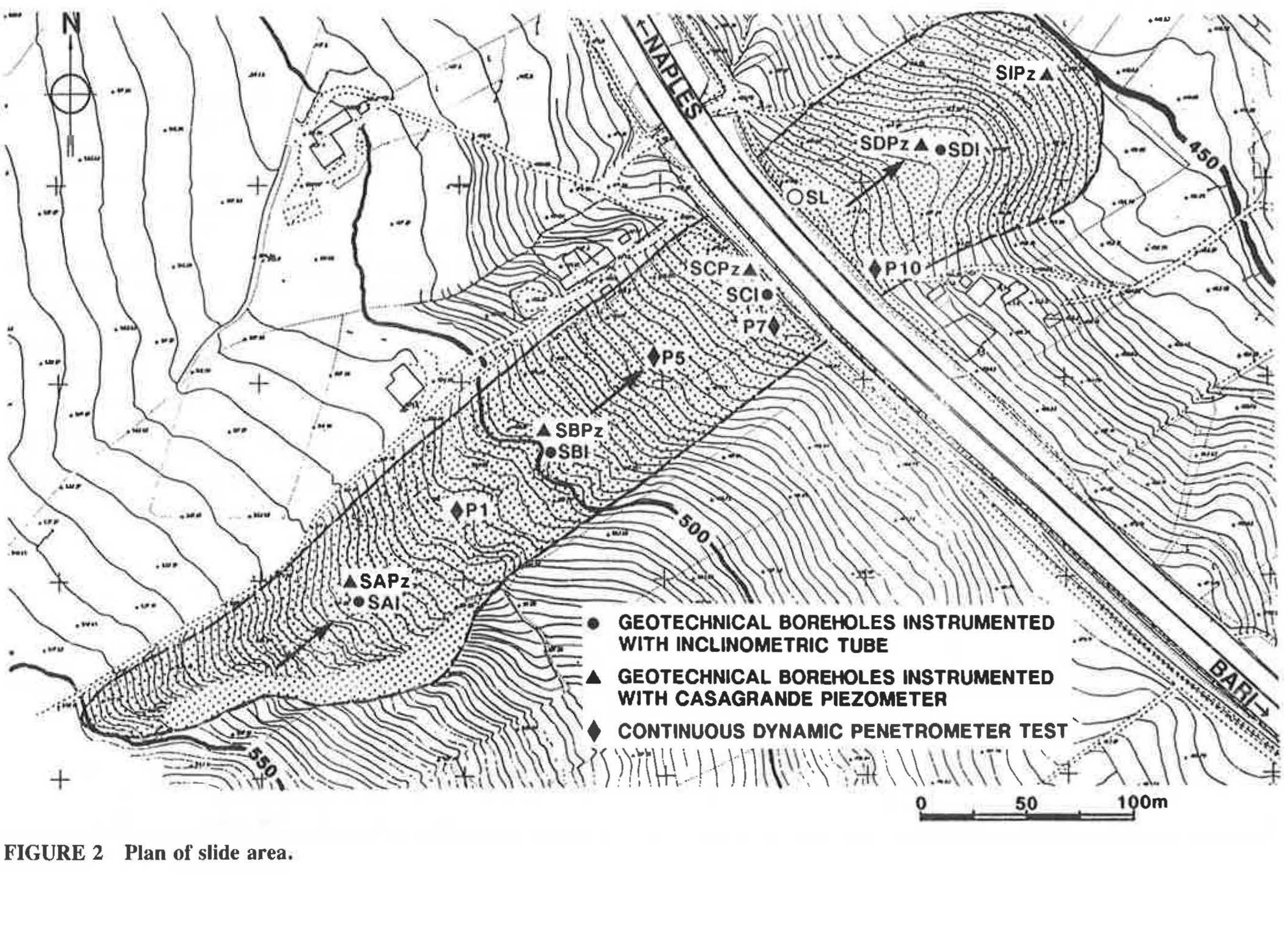

FIGURE 2 Plan of slide area.

soil in this area consists of an upper formation of brown soft clayey silt, 8.0 to 10.0 m thick, and a base formation of grey-blue marly clay. Gradation, index properties, and strength parameters of the two formations are shown in Table 1.

On the basis of the preliminary data (geomorphological analysis, boreholes, and penetrometer test profiles), we concluded that the area involved is indeed that defined in Figure 2, the slip surface developed along the interface between the clayey silt, and the marly clay formations. This conclusion appears to be justified by the following considerations:

- Penetrometric profiles and SPT values show a marked increase in resistance just below the interface (Figure 3);
- N_{SPT} values in the marly clay formation are always very high, ranging between 50 blows/ft to refusal (more than 50 blows/15 cm);
- The flow type of the landslide suggests the development of shallow slide surfaces; and
- Residual friction angles inferred from back analyses show a good agreement with the values obtained from the correlation in Figure 1.

Preliminary data therefore seemed sufficient for an "urgent" design. Fortunately, because the soil investigation was carried out as a part of a general monitoring program of the motorway network and the rate of movement was low, it was possible to wait for the results of the inclinometer readings before undertaking the remedial works.

The examination of inclinometer results (Figure 3) clearly showed a slide surface much deeper (19.0 m) than the one inferred from the preliminary data (10.0 m).

On the basis of the above example, we can make the following statements: If we do not have a sufficient data bank available, the design of urgent remedial works must be carried out with extreme caution. In this case the design should involve only works of temporary nature. The design of the final works should always be supported by the acquisition of the complete instrumentation data, particularly inclinometer data.

TABLE 1 SOIL PARAMETERS

	Upper Formation	Base Formation
Unified Soil Classification System symbol	CL-CH	CL-CH
Clay fraction (%)	35–40	38–43
Liquid limit (%)	45–50	48–53
Plasticity index (%)	27–29	28–30
Water content (%)	22–25	12–15
Unit weight of soil (kN/m³)	20–21	22–23
Apparent cohesion intercept (kPa)	150	>800
Effective angle of internal friction (degrees)	25–27	–[a]
Effective cohesion intercept (kPa)	0.0	–[a]
Residual angle of internal friction (degrees)	17–19	16–17
Residual cohesion intercept (kPa)	0.0	0.0

[a]Unavailable data

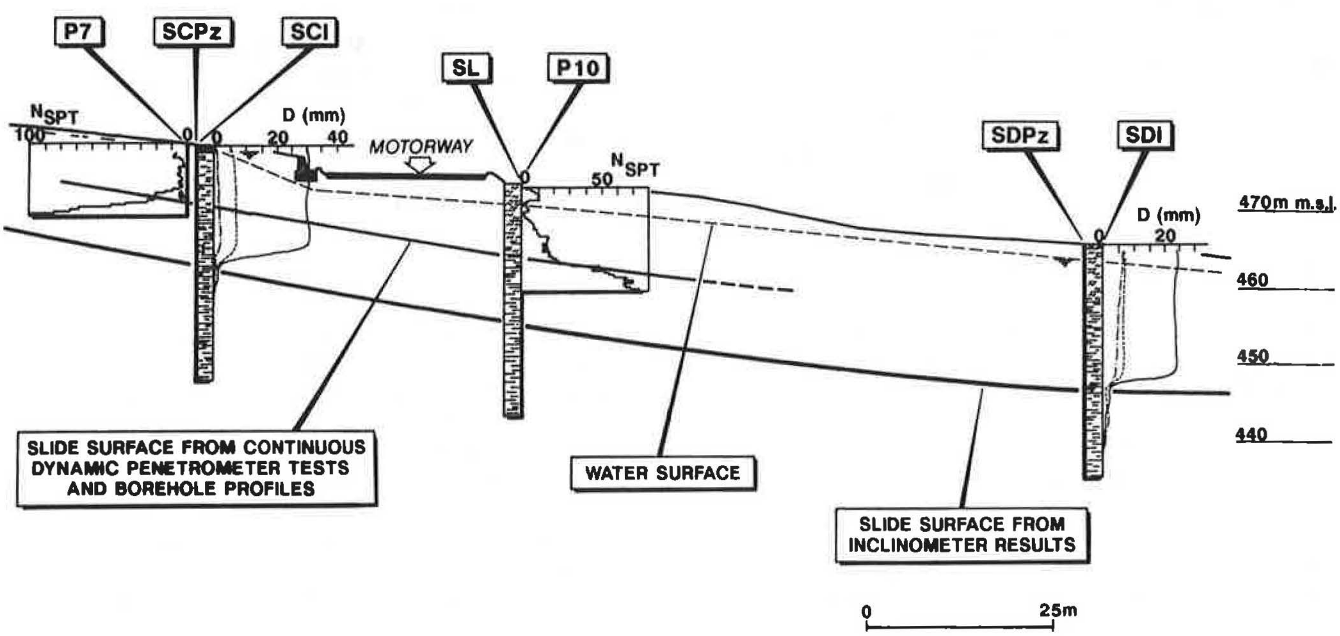

FIGURE 3 Typical section. *D* = horizontal displacement; dot-dashed line = December 14, 1987; dashed line = January 26, 1988; solid line = March 16, 1988.

It is the authors' experience that the time required for the acquisition of significant inclinometer data can be substantially reduced by operating with rigorous specifications concerning the technical characteristics of the instrumentation, tube installation, and the acquisition and processing of records.

Before showing the possible effects of instrumentation errors on the quality of the readings, it appears necessary to provide some definitions that will aid in understanding the material that follows.

- A reading is a set of measurements along the inclinometer tube;
- Measurement processing in terms of *integrated absolute displacements* gives the actual planimetric and altimetric position of each measurement point with respect to the vertical passing through the center of the tube toe;
- Measurement processing in terms of *integrated differential displacements* gives the tube deformation with respect to the initial tube profile corresponding to the "zero reading"; and
- Measurement processing in terms of *local differential displacements* gives the displacement at each measurement elevation, without integration. The displacements are with respect to the "zero reading."

The effects of possible instrumentation errors on the quality of the processed readings are shown in Figures 4 and 5, with reference to the landslide under consideration. From this information we can draw some useful conclusions:

- When data is processed in terms of integrated differential displacements (Figure 4), instrumentation errors can totally invalidate the final results or, at best, allow the determination of the slip surface depth only when large displacements are involved (15/03/1988 readings on Figure 4b and c).
- When data is processed in terms of local differential displacements (Figure 5), the instrumentation errors can be almost entirely overcome, thus allowing, in this particular case, the determination of the slip surface depth from the second reading, with a time savings of about 2 months.

Given the fact that in most cases the local differential method allows even rather significant instrumentation errors to be overcome, the best way to measure meaningful data quickly is by

- Reducing vertical deviation of the inclinometer tubes during the installation stage (< 1.5 percent);
- Using a biaxial inclinometer torpedo; and
- Performing periodic calibration of the equipment to determine the variations in the rotational shift of the sensor (small electrical or mechanical alignment shift of the sensor azimuth relative to the torpedo wheels) and in the sensitivity of the sensor and readout unit.

For situations in which the results of calibration tests are not available, the authors have adopted a procedure, consisting of the following steps, for an approximate evaluation of the variation in the sensitivity of the equipment and in the rotational shift of the sensor:

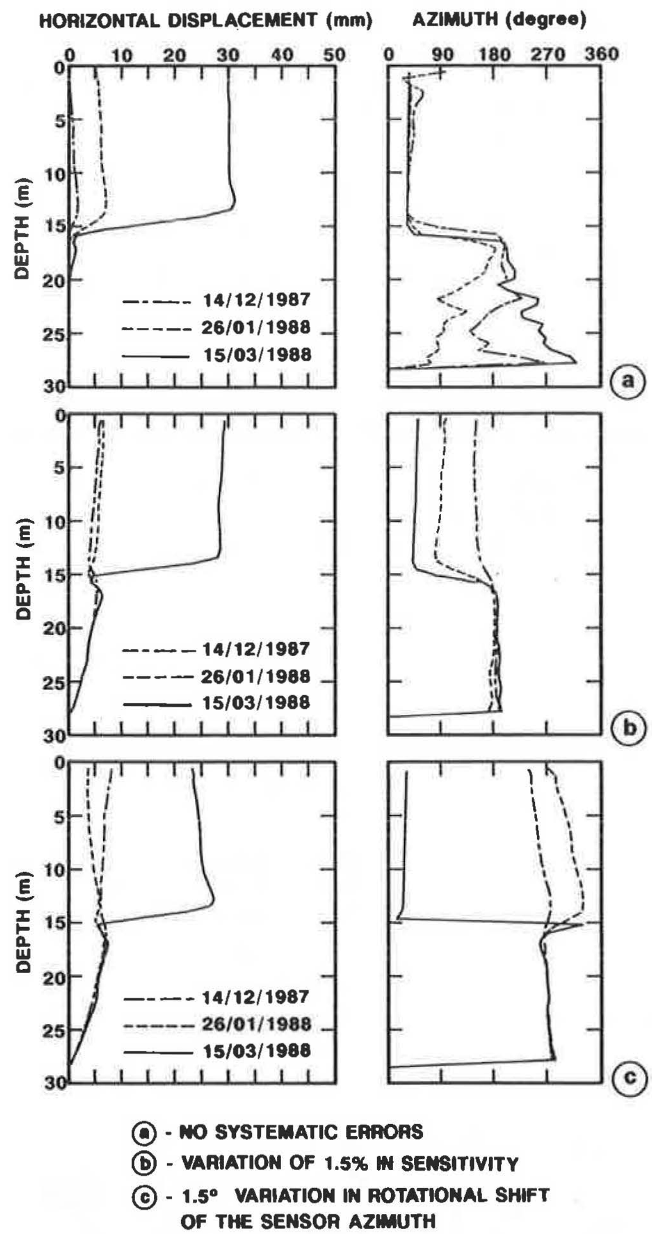

FIGURE 4 Measurement processing in terms of integrated differential displacements.

- Locating a short segment of the inclinometric tube that is certainly below the slip surface. This can be done in two ways: (a) by examining the stratigraphic-geotechnical data; (b) by performing a preliminary local differential elaboration of the readings. The latter procedure will, in general, produce a diagram similar to that shown in Figure 6. In this diagram, the lined area represents the sum of the systematic errors (variation in sensitivity and/or rotational shift), while the dotted area represents the shear zone deformations; below this zone, the soil is certainly stable.
- Processing data in terms of integrated absolute displacement (including "zero reading").
- Fixing a reference elevation (z) within the tube length below the slip surface. Given the fact that below the slip surface the absolute position of the point can not change with

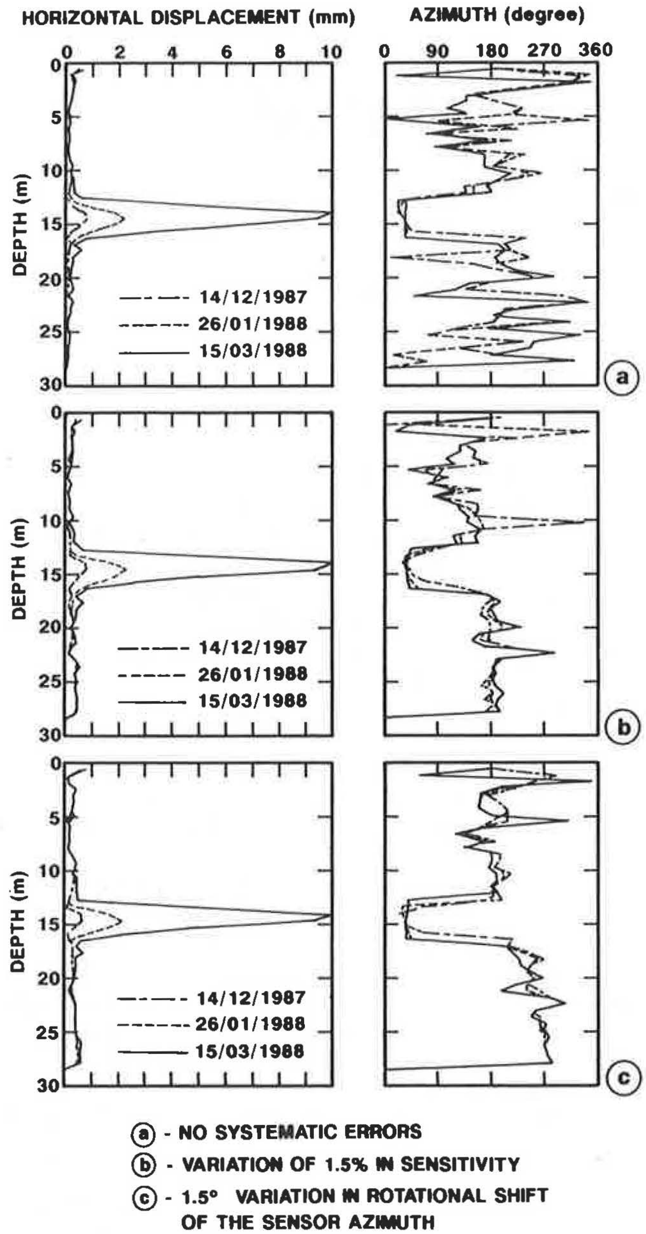

FIGURE 5 Measurement processing in terms of local differential displacements.

time, we can say that at the reference elevation, the ratio between the absolute displacement corresponding to the *n*th reading and the one corresponding to the zero reading gives the sensitivity variation of the torpedo and readout unit. Moreover, the difference between the azimuth values represents the rotational shift of the sensor.

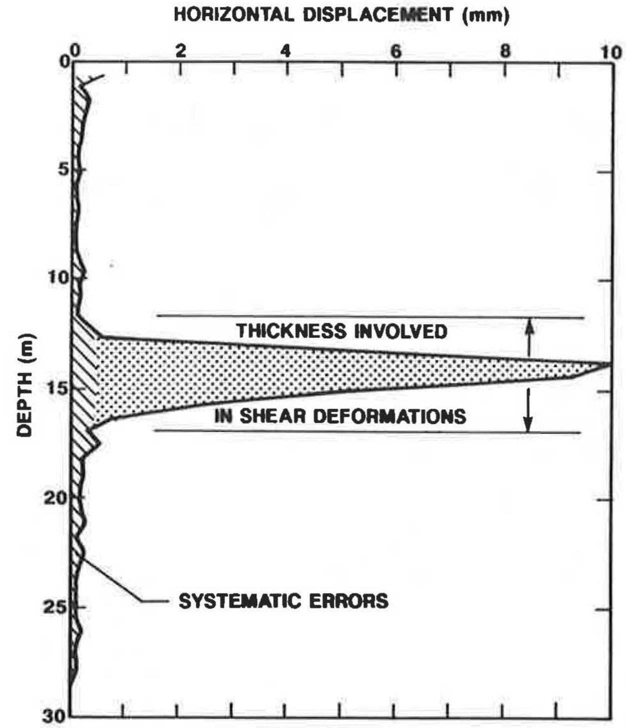

FIGURE 6 Determination of the soil thickness involved in the movement.

CONCLUSIONS

For a specific landslide, we have reported a misjudgment in the design of remedial works performed only on the basis of quick in situ tests. We recommend that the design of the final works should always be supported by the acquisition of complete instrumentation data, particularly inclinometer data. Moreover, we have proposed criteria to facilitate quick measurement of meaningful data. These criteria involve tube installation, reading equipment calibration, and measurement processing.

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