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Use of fixed inclinometers in the monitoring of landslides

L'utilisation d'inclinômètres fixes pour l'auscultation des glissements de terrain

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SYNOPSIS: This paper describes the experiments carried out in Perugia on the use of fixed inclinometric probes for monitoring deep displacement through the use of inclinometric tubes.
This method, originated initially from the need to have immediate continuous results, proved its effectiveness by furnishing quality results. After a brief summary of the geological-stratigraphical situation follows a description of the methods used for the processing and the representation of the curves obtained by the interpolation of the precise data measured. In conclusion, some remarks are made on the possible uses of this method, with a critical analysis of the criteria for installation and processing following the accumulated experience.

1 INTRODUCTION

The landslide phenomenon which occurred in 1982 on the hill of Perugia affected a highly urbanized zone and consequently required an extremely in-depth study in the analysis stage as in the reclamation project, but especially in the continuous monitoring of the kinematic characteristics of the landslide and of the static conditions of the buildings in order to verify the effectiveness of the reclamation operations.

The hill system on which Perugia is built is characterized, from a lithological-stratigraphical viewpoint, by great vertical and areal variability typical of deltoid facies, which does not allow one to obtain stratigraphical profiles for even limited distances despite the numerous drillings carried out. However, the following complexes are recognizable, from the bottom toward the ground surface:

-rocky basement made up of a Miocenic marly-arenaceous formation;

-silt and basal clays;

-sands, silts and clay seams interdigitated in lenses sharply inclined towards the valley;

-heterogenous deposits (sand and congolomerates) arranged in banks and lenses of considerable thickness;

-colluvial and fill material.

The movement referred to involved only the top three strata with variable depths up to 30 m from the ground surface.

The reclamation operation, carried out using vertical-type drainage systems connected to a bottom channel, was backed before, during and after the operation by a series of surveys and instrument monitoring . These controls consisted of piezometric, inclinometric and geodetic measurements, drainage output measurements, monitoring of the static conditions of the buildings, etc.

Since the type of monitoring described above are discontinuous, they are carried out at irregular intervals and time is needed for recording and processing, it follows that the recording of the event is not simultaneous with the occurrence of the event itself. Although this nonsimultaneousness is of little significance in slow-progress and time-constant phenomena, it becomes important when the event has accentuation or stasis characteristics (climatic or seismic events).

These considerations, together with the necessity of protecting public and private safety, have made evident the necessity of developing an emergency and safety plan for the zone. Therefore, it has become particularly important to have time-continuous monitoring which can guarantee safety with adequate warning time in case of sudden crises. A continuous monitoring and alarm system was thus created, consisting of various instruments placed in the landslide zone, read cyclically by peripheral units which transmit the data via cable to the concentrator located at the monitoring offices; here the data are recorded and processed in various ways.

2 THE USE OF FIXED INCLINOMETERS IN THE CONTINUOUS MONITORING SYSTEM

In periodic manual monitoring much attention was given to the inclinometric data which were read with extreme care and which provided very substantial indications as to the extent of deep displacements, their rate of movement, and to the very precise location of the shear surface. In fact, analyzing the data from manual readings carried out at 100 cm intervals, one notes how the inclination takes on very high values in the shear zones for two or at most three readings corresponding to a soil layer approximately 2-3 m thick.

The extreme vertical variability of sediments did not allow an exact and meaningful correlation between the slip layer and soil geomechanical characteristics in either quantitative or qualitative terms. Despite this, the individuation of the slip layer was always confirmed exactly from subsequent readings.

The need for having continuous readings of displacements taking place deep in the ground advocated the use of inclinometric probes placed in the ground at fixed depths equipped with sensors in two orthogonal directions and the study of suitable processing methods in order to reconstruct a continuous jagged curve of the tube taken from a fair number of punctual readings.

2.1 Positioning and installation criteria

The installation of fixed probes occurred after about two years of manual readings, consequently there was already a large volume of data on hand which allowed working in an extremely precise manner.

Out of all the installed tubes (approximately 30) which were being read manually at fixed intervals, those chosen were the ones which indicated the presence of a shear surface or at least a slip layer which was very precise and limited, such as to permit the following theoretical approximation:

-the displacement measured at the top of the tube occurs almost completely in relation with the slip layer.

After having individuated which tubes showed this behavior, new inclinometric tubes were installed in the immediate vicinity, at a distance such as to avoid disturbing the old tubes during drilling, and the fixed probes were positioned in the new tubes.

The probes are composed of a metal casing with two sensors placed inside at right angles (grooves A and B) for measuring the precise inclinations at the installation depth; the wheels attached to the probe body allow the exact positioning inside the tube in accordance with azimuthal directions precisely detectable from the orientation of the tube top guides and further corrected by the spiralometric survey.

The number of probes and the depths at which they are located were decided on the basis of the manual readings taken previously from the nearby tube on the basis of the considerations described in following. First of all, it was decided to position a maximum of 5 probes in each tube, because a higher number would have caused obstruction and size problems due to the several connection cables which must pass the upper probes, as well as because it was thought that a punctual survey at 5 depths would allow reconstruction of the actual curve of displacement in close approximation.

To verify this hypothesis previous to probe positioning, a digital simulation was carried out, defining the mathematical model which reconstructed the actual curve measured with readings at an interval of 1 m taken from 5 punctual readings. The 5 measuring points were chosen as follows:

1 at the top of the tube at a depth of 2 m from the ground surface, thinking that this depth would guarantee against disturbances at the ground surface due, for example, to vehicle traffic;

1 at the bottom of the tube to verify the absence of rotations at that depth, to confirm the validity of the operating principle of inclinometers and to test probe stability;

3 spanning the shear surface at 2 m distances from each other (a distance dictated mostly by size requirements since the probes are more than 1 m long), such that the middle probe would have recorded the maximum inclination variations and the outside probes much smaller variations. In theory these three central probes would be sufficient, with the slip believed to be concentrated in the layer delimited by the 4 m distance covered by the central probes.

2.2 Data interpolation criteria

The work was then divided into the following stages:

1) a hypothesis of the calculation model on the basis of previous readings;

2) verification of the chosen model by means of digital simulation and definition of the probe installation depth at the position thus determined.

Two different mathematical models were tested, according to the interpolation curve which approximates the jagged curve reconstructed from 5 known inclinations and from the absence of displacement at the foot of the continuously measured curve:

a) one quintic, for the entire length;

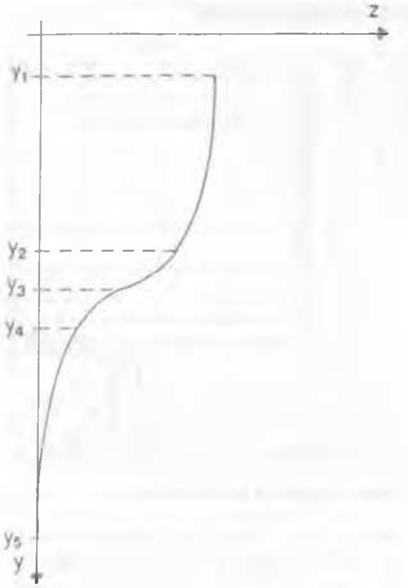
b) one cubic arc in the middle layer of the three central probes and two parabolic arcs in the upper and lower terminal zones.

The coefficients of the above-mentioned curve equations were calculated with the values of the 5 inclinations given by the instruments and attributing null displacement at the base probe. Once the coefficients are defined, the calculations are made of the horizontal displacements at fixed depth intervals in the directions of the two sensor orthogonal planes of the individual inclinometric probe (grooves A and B) and finally the vectorial sum of the displacements and the azimuth are calculated for each fixed depth.

By comparing these results it appeared that a fifth power curve does not fit the particular phenomenon in question because it prescinds, in the forming of points of inflection, from the specific shear zone previously individuated and therefore the processing results gotten from this curve provide only rough approximations of the actual situation.

The choice of a sum of curves (parabolic + cubic + parabolic, see figure 1) has the great advantage of focusing the point of inflection where it is actually occurring, and the approximation reached is far better (see figure 2).

In choosing representation by means of a sum of curves, the digital simulation allowed verification of the most suitable depths for positioning the probes. In fact, by comparing the data referring to depths 19-21-23



parabolic

$y_1 < y < y_2$

$a_8 y^2 + a_9 y + a_{10} = z_3$

cubic

$y_2 < y < y_4$

$a_4 y^3 + a_5 y^2 + a_6 y + a_7 = z_2$

parabolic

$y_4 < y < y_5$

$a_1 y^2 + a_2 y + a_3 = z_1$

boundary conditions

$z_3'(y_1) = \bar{z}_1'$

$z_3'(y_2) = \bar{z}_2'$

$z_2'(y_2) = \bar{z}_2'$

$z_2(y_2) = z_3(y_2)$

$z_2'(y_3) = \bar{z}_3'$

$z_2'(y_4) = \bar{z}_4'$

$z_1'(y_4) = \bar{z}_4'$

$z_1(y_4) = z_2(y_4)$

$z_1'(y_5) = \bar{z}_5'$

$z_1(y_5) = 0$

Figure 1. Interpolation curve equations

and 20-22-24 of inclinometer si9, it was noticed that the first choice, which coincides with the positioning of the middle probe in the point at which the greatest inclination values were measured, gives clearly better processing results, especially in the central slip range. Figure 3 shows the diagrams for the correct choice of depths at which to collect data on the punctual inclinations (19-21-23); in figure 4 a slight variation is illustrated (20-22-24).

A further investigation consisted of hypothesizing, independently of the field values taken, variations of null inclination of the curve at the top and at the base of the inclinometric tube, assuming a complete absence of displacement in these zones. An analysis of the results pointed out the slight influence of the inclination variations at the top and base, both in total displacements as well as in those of the middle slip layer. Thus the positioning of probes in the terminal zones is more for testing hypotheses rather than for better defining the curve of the displacements.

Table I shows the results of processing with and without inclination variations at the extremities; it can be seen that the resulting differences, in this case, are much less than the instrument tolerances.

The work then proceeded with the installation of probes inside the new tubes, checking the orientation of the sensors and being very careful about positioning the probe at the exact depth, coinciding with that given in the digital simulation calculation as shown above.

When installing the tubes and subsequently

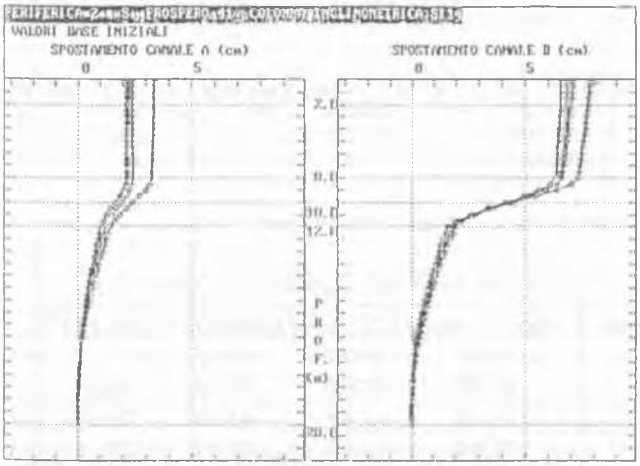


Figure 2A. Si14: displacement components

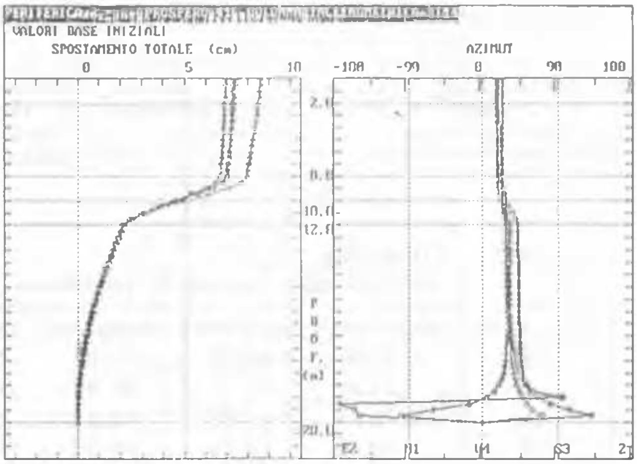


Figure 2B. Si14: total displacement and azimuth

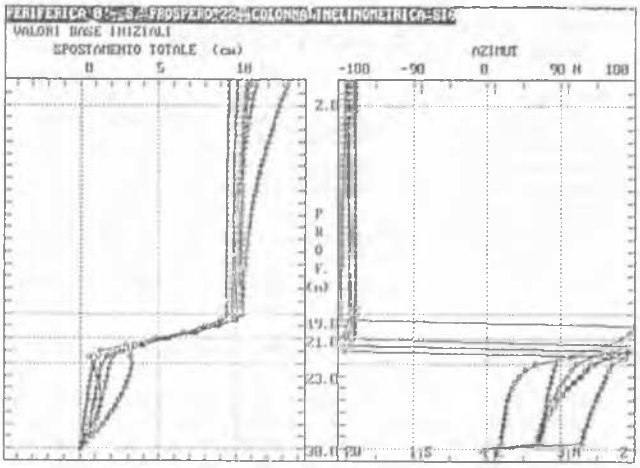


Figure 3: Correct probe depth positioning

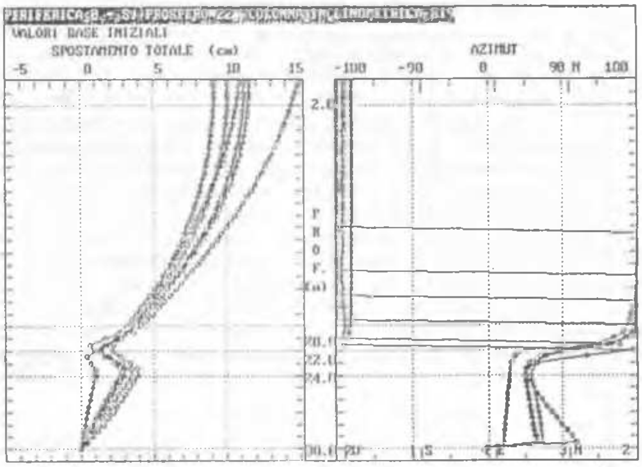


Figure 4: Incorrect probe depth positioning

the probes inside the tubes, all the procedures which concern the normal execution of inclinometric readings were followed.

3 GRAPHIC REPRESENTATION METHOD

For the display of the data recorded by the instrument a program was created which gives a double graphic representation for each inclinometric column, for days and for months.

The per day representation allows display of either inclinometer diagrams for a certain date or the superimposing on the display screen and subsequent printout up to seven diagrams from continuous days or days picked at random.

The per month representation instead allows the simultaneous display, once given the month and the year to be represented, of the graphs of each day in the given month by simply pushing one key repeatedly.

In both types of representation the initial reading is given as a base, but it is possible to refer diagrams to a date established a priori.

4 CRITICAL ANALYSIS AND CONCLUSIONS

It can be concluded from experience that by the positioning of a series of probes inside an inclinometric tube kept permanently in the same position, it is possible to have continuous monitoring of soil displacements, on the assumption of having determined a specific slip layer, and to construct a curve which closely approximates the actual tube jagged curve, especially in the shear zone, and thus provide worthwhile indications for the use of this instrument in a continuous monitoring and alarm system.

A further increase in the number of probes to be utilized beyond that already given does not seem necessary, accepting a priori a certain variance in the actual values recorded continuously especially in the zones outside the slip layer. If necessary, it makes sense to bring the outside sensors nearer to the shear zone, using an analogous law of interpolation when there is a definite invariance of inclination at the tube ends.

Furthermore, it does not appear that use of additional series of curves can better the close approximation already obtained.

REFERENCES

Balducci, M. (1986). Controlli strumentali delle aree e degli edifici interessati dalla frana di Fontivegge in Perugia, XVI Convegno di Geotecnica, 14-16 May 1986, Bologna, Italy.

Custodi, A., (1986). Un sistema di controllo continuo ed allarme per la frana di Fontivegge in Perugia, XVI Convegno di Geotecnica, 14-16 May, Bologna, Italy.

Table I.	Processing with inclination variation at extremities				without inclination variation at extremities			
depth (m)	disp."A"(mm)	disp."B"(mm)	tot.disp(mm)	azimuth(°)	disp."A" (mm)	disp."B"(mm)	tot.disp(mm)	azimuth (°)
2	22,05	65,65	69,25	18,56	21,05	65,85	69,13	17,73
8	21,60	63,10	66,69	18,90	21,20	63,90	67,32	18,35
10	16,65	41,62	44,83	21,80	16,25	42,42	45,43	20,96
12	10,40	18,40	21,13	29,48	10,00	19,20	21,64	27,51
28	0,03	- 0,03	0,04	131,55	0,01	0,02	0,02	27,51