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AN ALTERNATIVE APPROACH TO THE STUDY OF DEEP MECHANISM OF LARGE-SCALE MASS MOVEMENTS

ABSTRACT: RAINONE M.L., SCIARRA N. & SIGNANINI P., *An alternative approach to the study of deep mechanism of large-scale mass movements* (IT ISSN 0331-9838, 1996).

In complex large scale mass movements the presence of surficial deformations and/or displacements have never been used for the definition of deep mechanisms and their kinematics. The aim of the research in progress is to try to define a reproducible system, of study and analysis, of such phenomena, which can be applied to in complex geological-geomorphological situations.

The proposed methodology is based on aerophotogrammetry survey data; in particular from data obtained by pre- and post-event flights. The topographical variations of the subject area of a landslide can be modelled in a digital form.

Starting from simple models of different landslide typologies (rotational, roto-translational, etc.) and analysing the plano-altimetric variations, before and after the movements and the consequential distribution of displacement vectors, it was possible to create a preliminary classification of the type of slope movements, and to give some indications as to the probable depth of rupture surfaces.

The possibility of processing a complex landslide, by breaking it down into simplified kinematic models using polynomial fitting techniques or Fast Fourier Transform analysis and successive filtering steps, gives results of relevance for future research aims.

As real application of such a method we propose the example of the 1982 Ancona (Central Italy) landslide. A great deal of topographic data already existed regarding this large mass movement.

KEY WORDS: Large landslides, Topography, Aerophotogrammetry, Kinematics.

RIASSUNTO: RAINONE M.L., SCIARRA N. & SIGNANINI P., *Un approccio alternativo allo studio dei meccanismi profondi dei grandi movimenti di massa* (IT ISSN 0331-9838, 1996).

Nei movimenti gravitativi profondi complessi, i fenomeni deformativi e gli spostamenti superficiali non sono mai stati utilizzati per la definizione geometrica dei meccanismi e cinematismi profondi. L'obiettivo della ricerca in corso è di definire un sistema di studio che a partire da osservazioni superficiali, dia informazioni sui meccanismi profondi soprattutto in contesti geologico-geomorfologici complessi.

I dati, su cui è basato il metodo proposto, derivano da rilievi fotogrammetrici e topografici. Disponendo di voli pre e post evento franoso, è possibile modellare, in forma digitale, le variazioni topografiche subite dall'area interessata dall'evento gravitativo. La modellizzazione di tipologie di frana semplici (rotazionali, rototraslazionali, ecc.) in termini di variazioni planoaltimetriche pre e post evento e la conseguente distribuzione dei vettori di spostamento, hanno permesso una prima classificazione delle tipologie dei movimenti, fornendo inoltre indicazioni circa la possibile profondità delle superfici di rottura. La possibilità poi di trattare un movimento gravitativo complesso scomponendolo in modelli cinematici semplici (o semplificati) mediante tecniche di *Polinomial Fitting* o *Fast Fourier Transform Analysis*, consentirà di ottenere risultati di sicuro interesse per i futuri obiettivi della ricerca.

Come applicazione reale del metodo si presentano i risultati ottenuti dall'analisi, mediante tali tecniche, dei dati aerofotogrammetrici e topografici di superficie della grande frana di Ancona (Italia centrale) del 1982. Su tale movimento franoso già esisteva una ampia ed esauriente indagine topografica.

TERMINI CHIAVE: Grandi frane, Topografia, Aerofotogrammetria, Cinematica.

INTRODUCTION

The development of elaboration techniques for photogrammetric or topographical data currently make it possible to obtain a great deal of interesting information on the interpretation of deep phenomena. This is particularly true of urbanised areas, where measurement is more precise given the presence of infrastructures which, when subject to rotational and/or translational movements, can be easily surveyed. For each measurement the value of the single components of displacement, of which the level of uncertainty is known, can be indicated. These data are however characterised by considerable accuracy. Furthermore, thanks to current powerful calculating capacities the techniques of processing the data, such as polynomial best fittings, of the distribution of the signal at least squares positioning on a regular grid, have had a notable development.

In our case the method of positioning the displacement vector (vertical and horizontal) on the point of initial position of the zero vector gives us the possibility of assessing the trend and depth of the probable slip surface.

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The work was divided into three phases. The first consisted in the analysis of vectorial fields of movement of simple kinematic systems, assessing the possibility of obtaining the slip plane from analysis of surface displacement data. In the second phase the methodology of deep movement was made more complex with the use of real models. Finally, an application was carried out on the data of the topographical and aerophotogrammetric survey, with positioning on a regular grid, of the Great landslide of Ancona of 1982 (CUNIETTI & *alii*, 1984, 1986). The used example allowed us to make some considerations on the probable trend of the deep slip planes of this gravitational phenomenon.

ANALYSIS OF THE KINEMATIC SYSTEMS

The movement of a portion of slope along a particular surface is caused by the overcoming of the resistences typical of the material on the part of internal and external forces which act in favour of the generation of the same movement. Ignoring the concepts concerning the causes and analysing the effects produced by the movement, it is possible to base a type of classification of the landslide system on the type of kinematicism triggered by introducing some concepts regarding the dynamics of the movement, the energy consumed by the masses in movement, etc. In any case, it is the geometry of the slide plane which governs the phenomenon. This surface, more or less complex, also conditions, in materials with a rigid-plastic behaviour, the dynamics of the form of the topographic surface. For this reason, starting from a known slide plane, it is possible to obtain on the surface, with the movement in progress, a positioning of the topographic points which can be predicted and therefore surveyed and quantified. On the other hand, given the dynamics of the surface displacements, it is possible to obtain in the inverse manner, indications as to the form and depth of the slip plane. In order to do this one must start from the study of simple kinematic systems and progressively move on to more complex systems.

Simple systems

A simple kinematic system refers to a purely rigid movement of a portion of hypothetical slope which has a circular slip plane and a variable position of the centre of rotation.

With the centre of rotation belonging to the topographic surface, the portion of slope affected by the movement is naturally a semi-circle. With the centre of rotation positioned at the infinite the kinematism is precisely that of a pure translatory motion; in intermediate cases the portion of slope becomes the arc of a circle.

The analysed models were studied using a local, and not absolute, system of reference. In this way, positioning the origin of the system of reference at the starting point of the kinematic phenomenon (fig. 1), with the axis of the abscissa coincident with the mediate pre-movement topographic profile, the study can be carried out by normalising the problem with respect to the slope angle.

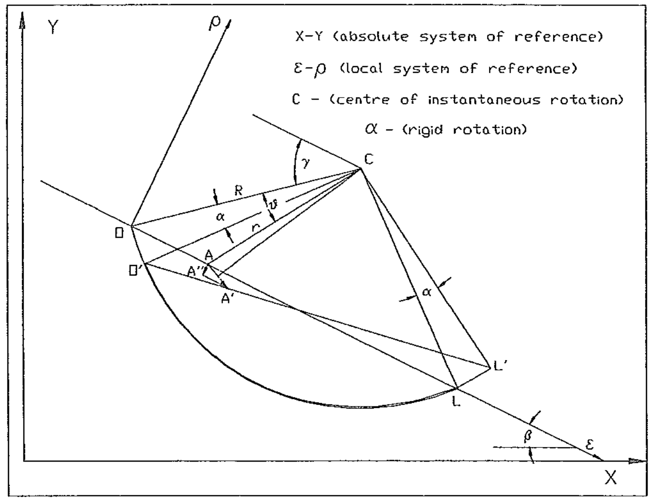


FIG. 1 - General scheme used for the representation of a simple kinematism.

Starting from the case of a randomly positioned centre of rotation, it is possible to analytically obtain, for each point on the topographic surface, the values of the modules of the vectors of vertical and horizontal displacement referred to the local system of positioning. In fact, the available topographic datum, derived from the processing of the data acquired through photogrammetry or classic topography, turns out to be, using the method of positioning, a representation of vectorial fields in which the displacement vectors, arranged in a regular grid and after appropriate filtering, give a picture of only the surface dislocation of the masses involved. The classic representation is that of illustrating diagrammatically the difference between the vectors relative to two temporal positions in Cartesian co-ordinates, according to the cartographic reference.

Fig. 1 hypothesises a rigid rotation in the circular section of chord OL surrounding the centre of instantaneous rotation C. Point A is identified by knowing the radius (R) of the circumference and the angle θ. Let, furthermore, γ be the angle between the sides *OC'* and the chord *OL* and α is intended as the rigid rotation of the circle. Following the rigid rotation, point A will be at point A'. The displacement vector *AA'* can be broken down into the two components AA" and A"A', whose modules are given by:

$$\Delta\varepsilon = |A''A'| = R\,[\cos(\gamma+\theta) - \cos(\gamma+\theta+\alpha)]/\sin(\gamma+\theta) \quad (1)$$

$$\Delta\rho = |AA''| = R\,[\sin(\gamma+\theta+\alpha) - \sin(\gamma+\theta)]/\sin(\gamma+\theta) \quad (2)$$

These dimensions are known as they are obtainable with topographic methods. Furthermore the local co-ordinates of A and A' are respectively:

$$\varepsilon = R[\cos\gamma\,\sin(\theta+\gamma) - \sin\gamma\,\cos(\theta+\gamma)]/\sin(\theta+\gamma) \quad (3)$$

$$\rho = 0$$

e

$$\varepsilon = R[\cos\gamma\,\sin(\theta+\gamma) - \sin\gamma\,\cos(\theta+\gamma)]/\sin(\theta+\gamma) + \Delta\varepsilon \quad (4)$$

$$\rho = \Delta\rho$$

Obtaining the equation of the straight line joining points A and A' and calculating the equation of the normal straight line at the latter and passing through the mean point of the segment AA', it is possible to obtain the equation:

$$\rho = \lambda\, \varepsilon + \psi \tag{5}$$

in which:

$$\lambda = [\mathrm{cotg}(\gamma+\theta)-\mathrm{cotg}(\gamma+\theta)\cos\alpha+\sin\alpha]/[\cos\alpha + \sin\alpha\, \mathrm{cotg}(\gamma+\theta) - 1] \tag{6}$$

and

$$\psi = R \sin\gamma \{[\cos\alpha + \sin\alpha\, \mathrm{cotg}(\gamma+\theta)-1]^2 + 2\, [\mathrm{cotg}(\gamma+\theta)\, (1-\cos\alpha)+\sin\alpha] \{[\mathrm{cotg}\gamma - \mathrm{cotg}(\gamma+\theta)] + [\mathrm{cotg}(\gamma+\theta)(1 - \cos\alpha) + \sin\alpha]\}\} / \{2\, [\cos\alpha + \sin\alpha\, \mathrm{cotg}(\gamma+\theta) - 1]\} \tag{7}$$

This equation is valid starting from each point on the chord OL. Furthermore, all the straight lines of equation (5) intersect at point C, which represents the instantaneous centre of rotation of the simple kinematism.

Fig. 2a shows how the ratio $\Delta\varepsilon/\Delta\rho$ varies in function of α for different values of θ once the value of γ is fixed. In particular for limited rotations, between 1° and 5° (fig. 2b), the ratio is practically constant; in the extreme case of

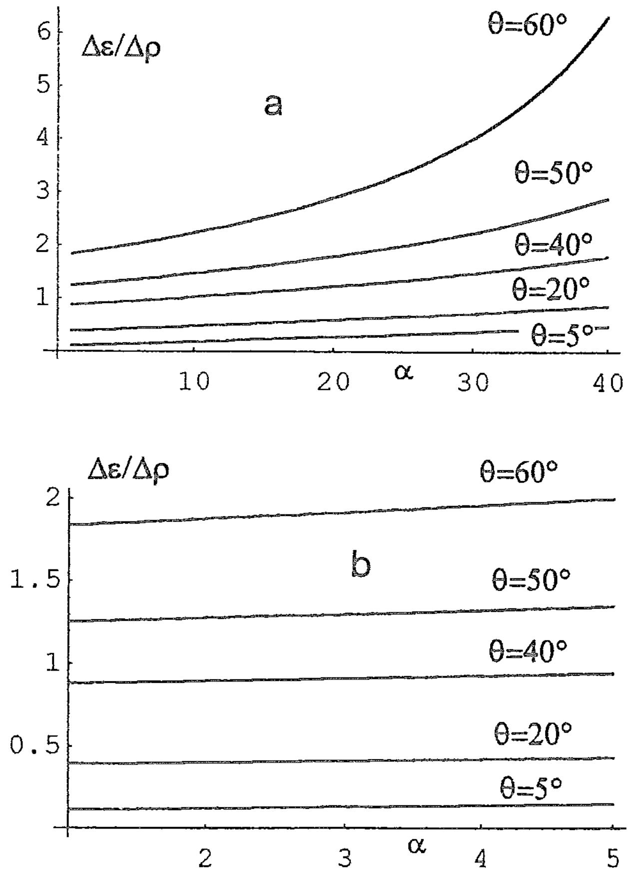


FIG. 2 - Variation of $\Delta\varepsilon/\Delta\rho$ in function of α for different values of θ; (a) for the entire field and (b) for small variations of α.

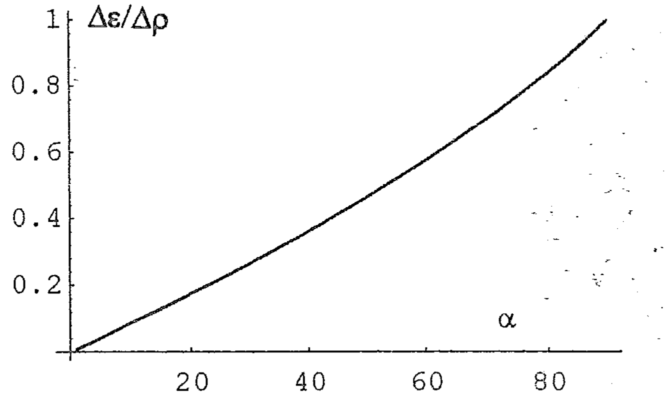


FIG. 3 - Variation of $\Delta\varepsilon/\Delta\rho$ in the extreme case of $\gamma = 0$.

$\gamma = 0$ (semi-circle) there is no sense speaking of different values of θ. In fact, the ratio $\Delta\varepsilon/\Delta\rho$ is equal to (1-cos α) /sen α and consequently is a function only of α (fig. 3). In this specific case ($\gamma = 0$), for $\alpha < 5°$, the ratio $\Delta\varepsilon/\Delta\rho$ remains practically constant for the vectors of the entire field and the relative value is equal to 0.04. The movement that results is of a rotational type and therefore it is possible, knowing the surface limits, to estimate immediately the depth.

On the other hand, still for limited rotations, should the ratio $\Delta\varepsilon/\Delta\rho$ assume greater values, it is possible to assess the position of the centre of rotation and therefore estimate the depth of the rupture surface.

Complex systems

Complex kinematic systems are those movements of portions of slope along surfaces of any form. A complex kinematic system (fig.4) can be interpreted as the sum of a series of simple kinematisms interpolating the sections superimposed on the arcs of a circle due to instantaneous centres of rotation which move in any direction.

In this sense, it must be specified that a complex model is that in which the vectors of surface displacement give an indication of various instantaneous centres of rotation. There is no consideration taken, therefore, of the concept

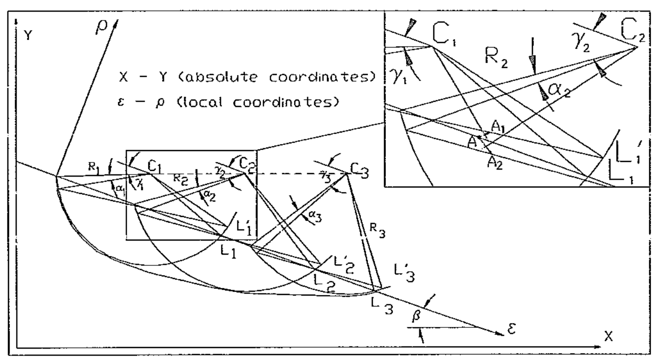


FIG. 4 - General scheme of the possible evolution of a rupture mechanism as a sum of simple mechanisms.

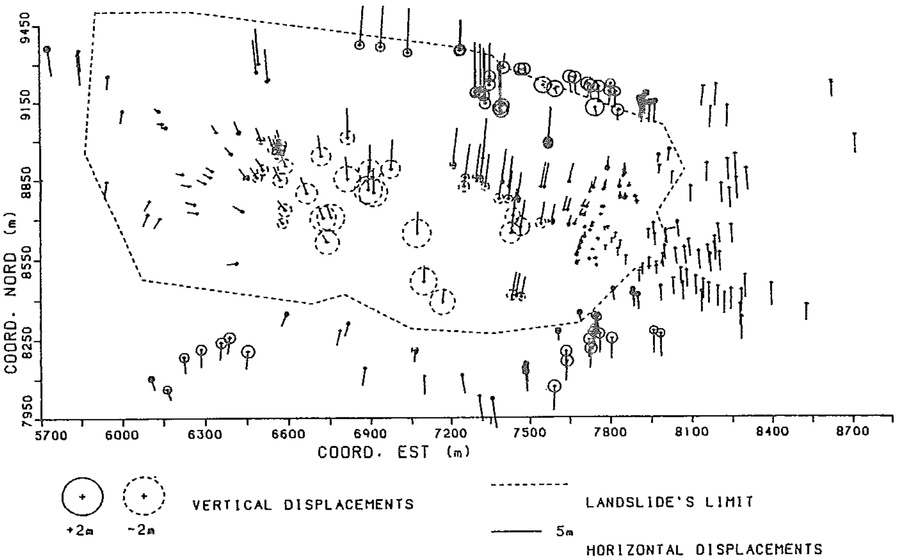


FIG. 5 - Distribution of the signal, obtained by processing at least squares location, of the planimetric and altimetric displacements measured on man-made structures (from CUNIETTI & *alii*, 1986).

of complexity from the point of view of the typology of the stresses present in the mass in movement.

For every circumference it is possible to use the same procedures described in the previous section. It is clear that the ratio $\Delta\varepsilon/\Delta\rho$, in the zones of superimposition of the various circles, should be studied in function of the relative position of the instantaneous centre of rotation.

In the zones of superimposition between two circles it is possible, due to kinematic congruence, that an area of lifting occurs. Geomorphologically such mechanisms, associated with the depression upslope, have as a result the definition of a trench. However, whatever the point of position of the vector of displacement is (detail of fig. 4), the method proposed indicates that there is still a link between this vector and a centre of instantaneous rotation.

APPLICATION OF THE MODEL TO A REAL CASE

The methodology described above was first applied to the «Great landslide of Ancona of 1982» (CRESCENTI & *alii*, 1983; COLTORTI & *alii*, 1984; CRESCENTI, 1986) on which, furthermore, there is a good amount of topographical discussion, including also minimal squares positioning on regular grids of data obtained with aerophotogrammetry. These data are the result of the altimetric and planimetric displacement of the observable man-made structures (COLOMBO & *alii*, 1985) preceding and following the landslide of 13 December 1982. Figs. 5 and 6 represent the procedure adopted to which further processing has been applied by means of the change of co-ordinates using a local system of reference, posi-

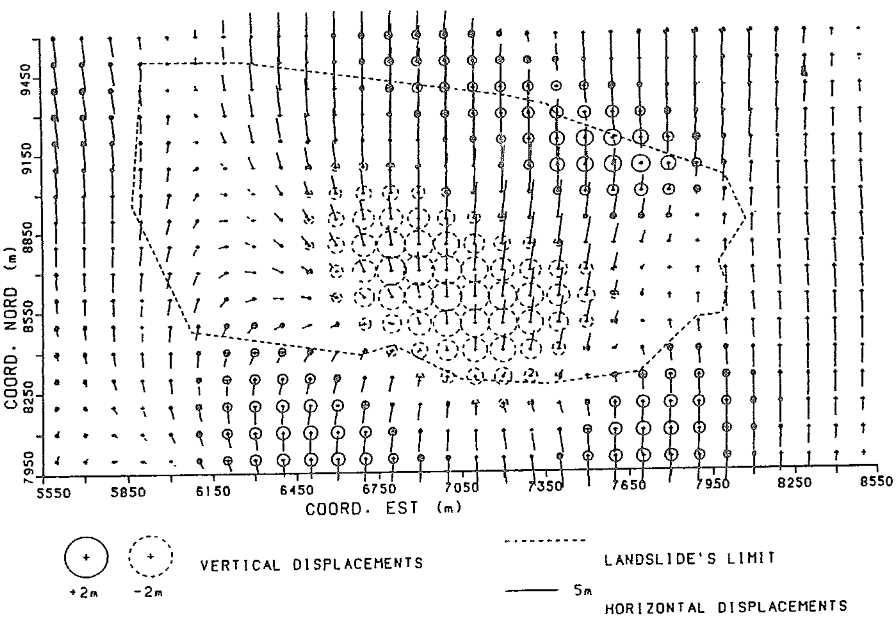
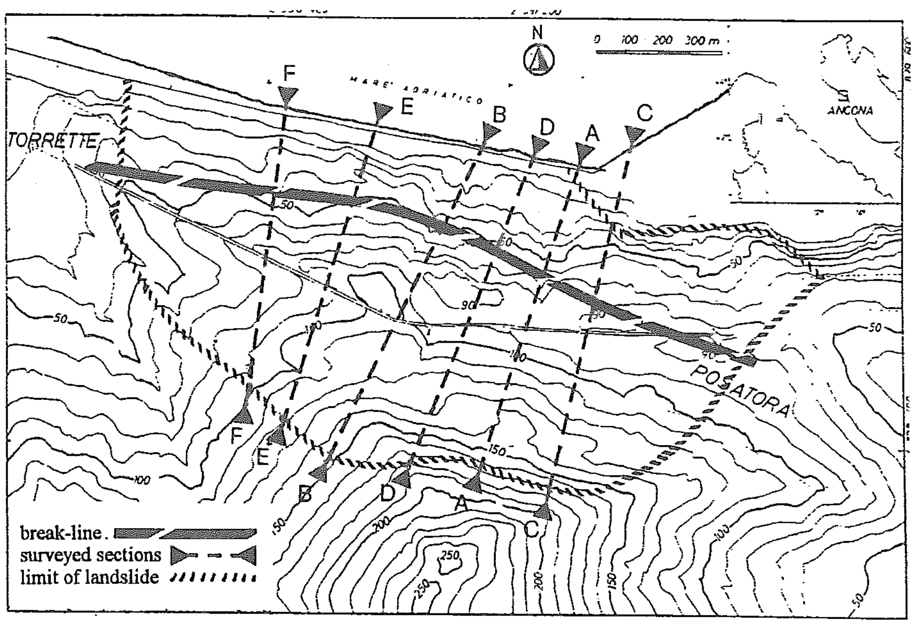


FIG. 6 - Distribution of the above mentioned signal at least squares location on a regular grid (from CUNIETTI & *alii*, 1986).

FIG. 7 - Map with surveyed profiles.



tioned in the highest point of the main scarp of the landslide.

This change, taking into account the low topographic gradient and the quite regular morphology, did not provoke substantial modifications to the vectorial field. Furthermore, a regionalization of this vectorial field was carried out with a method of moving mean in order to minimise the local effects.

The profiles selected for sections to analyse were purposely traced orthogonal to the break-line which represents, in plan, the place of intersection between the pre-landslide topographic surface and the post-landslide surface, or rather the line on which the modules of the vertical vectors of displacement are inverted.

Various profiles were analysed (fig. 7). The results obtained in sections A-A' and B-B' are reported. These seem to summarise most significantly the methodology we propose.

Profile A-A'

The section (fig. 8) presents a mainly rotational mechanism in the part upslope and in the valley and a planar movement in the intermediate section. This is evident from

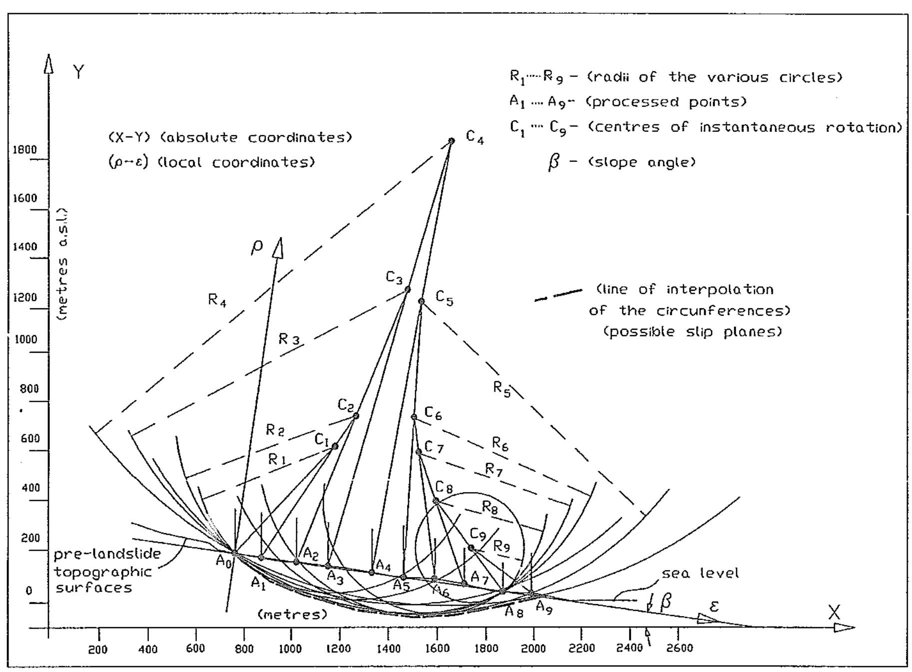


FIG. 8 - Results of the application of the method in section A-A'.

the distancing of the centres of instantaneous rotation from the topographic surface up to point C_4 and then their successive re-approach. The maximum depth reached is between the measured points A_4 and A_5 and is about 148 m. In the lower part the circumferences of radius R_8 and R_9 justify the possibility of the presence of some trenches in the intermediate section of the slope.

Profile B-B'

This section (fig. 9) shows a classic kinematism of the rototraslatory type pointing to a conchoidal surface with variable radius of curvature. The migration of the instantaneous centre of rotation is congruent with the variation in radius. Between points A_5 and A_6 the trend of the normals at the mean points of the vectors is divergent. This indicates that in the lower part of the slope the instantaneous centres of rotation are generated according to a mechanism similar to that proposed in complex kinematic models. The line that encompasses the various circumferences reaches a maximum depth from the topographic level of about 180 m.

The results show a good correspondence with those obtained in studies and surveys carried out in the area by various authors (CRESCENTI & *alii*, 1983, COLTORTI & *alii*, 1984; CRESCENTI, 1986).

CONCLUSIONS

The methodology proposed showed the possibility of using topographic and aerophotogrammetric data, to obtain information on the trend and depth of the slip plane(s) of a gravitational mass movement.

Starting from a simple kinematic model given by the rigid rotation of a circular sector and considering the vectors of surface displacement in directions ε, ρ, on a local reference plane (fig. 1), it was possible to obtain, analytically, the centre of instantaneous rotation of the mass in movement and, therefore, the trend of the slip planes using the method of intersection between the normals at the mean point of the displacement vectors. From a simple model we passed on to a more complex model considered as the sum of simple models.

This method was then applied to the «Great landslide of Ancona», using the existing data (processed with appropriate filtering and location on a regular grid) which represented the vectors of vertical and horizontal displacement of a material point on the surface. Our application consisted in starting from these data, changing the system of reference from absolute to local and applying the above described method with the aim of obtaining the slip planes along some significative sections.

The results obtained sometimes showed a good correspondence with the mechanisms known and hypothesised for the Ancona landslide. Various profiles were surveyed. In particular the results of the two most significative sections (A-A' and B-B') are reported.

Along these sections, the obtainable deep slip planes are coherent with those surveyed by the geognostic surveys. In the case of section A-A' the kinematism cannot be well interpreted as a system composed of simple systems, probably due to a not optimal processing of the topographical data for the aims prefixed by us. It is however possible to assert that, subjecting the original data to processing operations specifically aimed at the purposes of our research, situations of a particular complexity can be defined and resolved.

The presented method, which proposes a particular geometrical construction for the definition of the trend of the slip planes of a deep movement, must however use the results of the detailed geomorphological survey in the

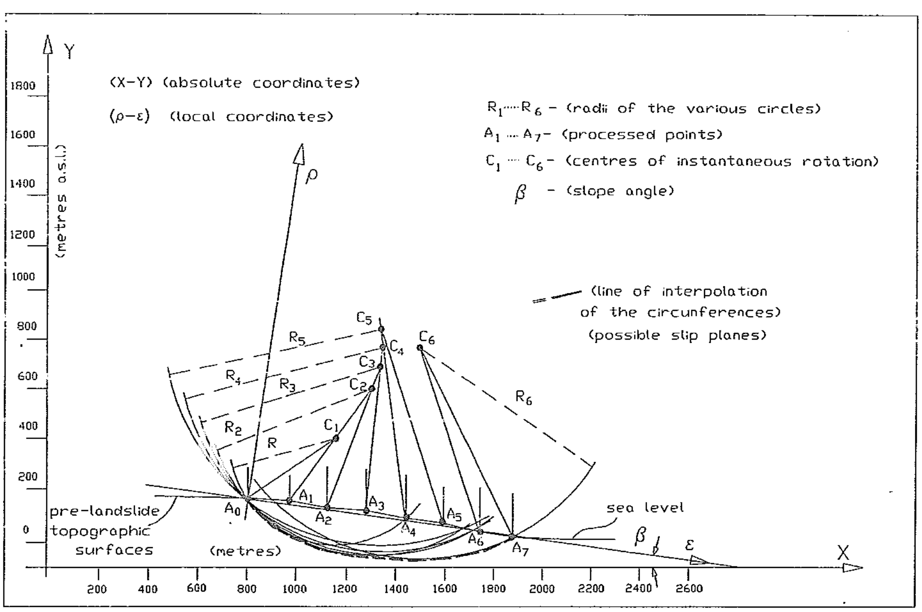


FIG. 9 - Results of the application of the method in section B-B'.

study area. The dimension of the radii of curvature must be adjusted on the basis of the surface verifications, along the slope, of the unequivocal indications of the presence of principal and secondary niches of detachment associated with the deep movement. A careful geomorphological reconstruction is essential for successful application of the method.

It is our opinion that the methodology proposed can also be useful in the initial phases of a study of a gravitational movement, indicating in a more precise manner the lines of investigation in particular as regards the extent of surveying required.

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