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CORRELATION BETWEEN RAINFALL AND LANDSLIDES

CORRÉLATION ENTRE CHUTES DE PLUIE ET GLISSEMENTS DE TERRAIN

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Abstract

Old landslides in precarious conditions and new masses are moved or removed by particularly heavy rainfalls. Phenomena relative to rock slides and earth slides are examined to evaluate the relations between mass movements, rainfall and interstitial pressures.

After a description of some mass movements taken from the literature, an analysis of some geological examples of landslides occurred in Tuscany Region (where instrument systems are) is carried out in order to research the value of the critic pluviometric threshold for which there is a geological hazard of sliding.

Résumé

D'anciens glissements de terrains instables ou des glissements nouveaux sont mis ou remis en mouvement par des chutes de pluie particulièrement fortes. Des phénomènes concernant des glissements de sols et de roches sont étudiés par les auteurs pour évaluer les relations entre les mouvements de terrain, les chutes de pluie et les pressions interstitielles.

Après avoir rappelé quelques glissements déjà étudiés dans la littérature, les auteurs analysent quelques exemples de glissements qui se sont produits en Toscane et, dans lesquels, des appareils de mesure ont été mis en place, le but visé étant de trouver la valeur du seuil critique au-delà duquel un glissement risque de se produire.

Introduction

Independently of mechanics, gravitational phenomena always take place in concomitance with important meteoric events.

Many authors have therefore sought to pinpoint correlations between landslides and rainfall, working in different geological and climatic environments.

R.H. Campbell (1975), in his studies of debris landslide phenomena in the Los Angeles area, pinpoints as dangerous those events that are of an intensity greater than 10.5 inches.

Nilsen, T.H. Taylor F.A. and Brabb E.F. (1976), working in Alameda County, California, have observed that landslides occur frequently in the presence of precipitations greater than 7 inches (18 cm) and that storms taking place after rainy periods are more dangerous.

The I.R.P.I. Institute of Turin of the National Research Council of Italy, working in the same field, reports that mass movements as thick as 10 m in marly-arenaceous units occur when the amount of cumulative rainfall in a 1 to 3-day period exceeds 100 mm (Govi, 1976).

Guidicini G. and Iwasa O.Y. (1977), working in Southeast Brazil, where heavy rains take place as the result of polar cold fronts, observe that landslides are generally due to events of an intensity varying between 12% and 18% of the annual rainfall; if the intensity surpasses 20%, catastrophic events result. In order to quantify these phenomena, the authors themselves suggest two coefficients: the "cycle coefficient C_c" and "the event coefficient C_e", expressed by the relation among "the cumulative precipitation record up to the date of the event", "the precipitation record of the event" and "the mean annual precipitation". The risk threshold may be estimated by "the final coefficient C_f" which is the sum of C_c and C_e.

Mazolai 0. (1980), comparing the landslide situation of the province of Trent in the ten-year period from 1966-67 to 1976-77 points out as a condition of instability the occurrence of intense events lasting 2-5 days, preceded by an especially humid season.

More detailed estimates on rainfall intensity accumulated over 3 and 4 days and in a 48-hour period were carried out by Sorzana P. (1980) during a study of the Arnulfi landslide.

Ceccarini F., Focardi P. and Zanchi C. (1981), studying the relationships among the shifts of a slide situated in the Mugello (Florence), the oscillations of the water table and the meteoric events, express a relationship among these phenomena by means of a coefficient, the "antecedent precipitation index, API":

$$API_n = \sum_{i=1}^{n} (P_i - Rs_i) K^{n-i}$$

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in which n is the progressive number of days; P_i is the depth of rainfall in mm taking place on a given day (i th); Rs_i is the surface rill in mm; and K is the recession constant assumed as equal to 0.90.

Landslide Test Sites

An examination has been made of four landslides already described in the literature that took place in Tuscany, in the province of Florence and Pistoia, in various years, in differing geological and climatic environments, occurring in materials of primary or secondary permeability from medium to high. They are:

The Fosso Falterona Landslide

In February 1960, in the vicinity of Castagno di Andrea (Village of S. Godenzo, Florence), about 5 million cubic metres of debris fell with a roar on Fosso Falterona, which lay below. From the geological investigations it was pointed out that the landslide had taken place in a thick layer of prevalently arenaceous debris. The material originated from the breakdown of the "marly-arenaceous unit" which consists, lithologically, of an alternation of sandstone levels of variable thickness, for the most part of marly schists, with horizontal layering.

The phenomena occurred at the head of the Fosso Falterona basin (12 km^2), in a mountainous area of the Northern Appennines, near the peak of Mount Falterona (1,654 m), on a slope whith an average inclination of 45°, that extends from an altitude of 1,360 m to an altitude of about 1,000 m.

The landslide, classifiable as a debris slide, was 700 m long and as wide as 200 m in the crown area. The slide debris originated in a debris flow along the Fosso Falterona for a length of about 1 km, descending down to an altitude of 800 m.

The landslide event occurred on 26 February, following upon a series of intense rains, of a height of 86 mm, which fell on 23 February (Grazi S. 1966).

The Fontelucente Landslide

The Fontelucente landslide occurred on November 4, 1966, following intense precipitations which caused the overflow of the Arno river and the Florence flood. The site is located a few kilometres from Florence, beneath the hill of Fiesole (Collina di S. Francesco, 345 m.).

The landslide involved about 20,000 cubic metres of rock and brought about the collapse of two buildings. The landslide movement is classifiable as a translational slide and occurred with rapid shifts (40 m in 1-2 hours). The slide material was composed of layers of sandstone and siltstone ("Macigno" formation) which was distributed along a bedding plane with a 20° inclination.

The crown was located at an altitude of 250 m; the foot at 180 m; its length was 225 m, its average width 50 m. The average inclination of the slope prior to the slide was about 25°.

The slide occurred in correspondence with a rainfall of exceptional intensity for that area (142.8 mm in one day) (Focardi P., 1969).

The Piastre Landslide

The Piastre landslide (site located near Cireglio, on the Appennines of Pistoia) occurred on 24 February, 1968. It involved about 30,000 square metres of earth material and cut off the State route n. 68 for about 200 m. The slope affected by the slide is situated in the rise of the Colli di Meleto, which has an altitude of about 800 m, where there are sandstone outcrops of the Macigno formation. Right below the slide the "Vincio di Cireglio" torrent flows, in whose bed the slide material was deposited.

The landslide has features similar to those of Fontelucente slide, consisting in a translational movement on a bedding plane with a slope varying between 20° and 27°. The crown is situated at an altitude of 705 m, the front at an altitude of 675 m.

The movement of a mass occurred two days after heavy daily precipitations of 153 mm (22 February).

The Marcialla Landslide

The slide is situated at a small distance downhill from the village of Marcialla (Certaldo, Florence) on a hill formed of Pliocene marine deposits, composed of pebbles and sand with silty intercalations.

The environment is characterized by small rises, with maximum altitudes of about 400-425 m. The central residential area of Marcialla, which corresponds to the top surface of the slope affected by the landslide, is about 384 m with slopes of medium acclivity, interrupted by escarpments and crags due to the alternation of different rocktypes.

The phenomenon, classifiable as a rotational slide, affects an area already subjected to an older landslide of which the new one represents its extension toward the upslope. The crown is situated at an altitude of 370 m, with a front at 313 m; the maximum length is about 180 m; the maximum width is 60 m.

Immediatly uphill from the crown, at the summit of the slope, there is a large lens of pebbles and gravel which holds the water table that almost immediately feels the effects of precipitation patterns.

The landslide presented its first manifestations in the days from 12 to 18 April, coinciding with intense precipitations, but underwent a rapid collapse, on the night of the 25th, due to other precipitations (Focardi P., Garzonio C.A., 1983).

Analysis of rainfall

In order to study the effect of rainfall on the 4 landslides, the pluviometric data, published by Arno Hydrographic Service, of the stations in the vicinity of the various slide sites, were analyzed. For the Fosso Falterona slide an analysis was made of the data recorded by the Castagno station (altitude 295 m; distance 0.5 km); for the Piastre slide those of the Cireglio station (altitude 630 m; distance 2.0 km); for the Marcialla slide those of Montespertoli station (altitude 257 m; distance about 8 km); for the Fontelucente slide those of Fiesole station (altitude 295 m; distance 0.5 km). The rains that caused the various slides were studied by adding up the episodes at 5-day intervals and by starting the cycle from the dry period that preceded the landslide event (1 July).

In the diagrams of Fig. 1BD, 2BD, these figures have been given along with the average annual rainfall measured at the respective stations. In each diagram there has also been given, on a conveniently enlarged scale, the daily cumulative pluviometric data which were responsible for the instability.

In order to estimate the repetitiveness of the events which were responsible for the landslides in the period in question, it was thought useful to make a statistical study, at the pluviometric stations, of the distribution of the intense events.

There were taken in to examination observations of the maximum annual precipitations for the duration of 1, 2, 3, 5, 15 and 30 days.

The maximum heights of the annual rainfalls recorded at each station were interpreted by the law of Gumbel. In this way it was possible to determine the return period, as expressed in years, of the heights of rainfall related to the various durations taken in examination. The lines interpolating the value points which represent the observations were recorded on probability paper (Fig. 1AC, 2AC), in which markings represent the precipitation events connected with the landslides (triangles) and the values of the precipitations of 4 November, 1966 (points); exceptional values in the entire area of Tuscany.

From observation of the lines concerning the Castagno station (Fig. 1A), it is noted that the events connected with the Fosso Falterona landslide have a relatively low recurrence, notably surpassed by these related to 4 November, 1966 (193 mm in 1 day; 249 mm in 3 days) and by those related to February, 1951 (and therefore prior to the year of the landslide, which was 1960), in which 155.6 mm fell in 1 day, 204 mm in 5 days. The values of February, 1960, tend toward greater return period as the length of time increases, reaching the maximum value of 15 days (263 mm), a value surpassed only by the precipitations of February, 1951 (284 mm), which represent the most intense precipitations recorded prior to the landslide.

A comparative analysis of the rainfall pattern in the days preceding the landslide and the statistical diagrams (Fig. 1AB) point out that, for the coarser debris materials like those involved in the Fosso Falterona accident, events having at least a 2-week duration need to be examined.

The diagrams of the cumulative curves of the Fiesole station show that, from 25 to 27 October, 66 mm of rain fell; subsequently there was a period of mild events until 3-4 November. On that occasion 143 mm of rain fell, representing an exceptional figure never recorded before by that station. The point distribution in the diagram in Fig. 1C (triangles), in particular those related to rainfalls of a 1 to 2-day duration, show extremely high recurrence periods; even the precipitations concerning the 15 to 30-day intervals prior to the triggering of the Fontelucente landslide show up as rather high, but over 50% of the mm of these intervals concern events lasting from 1 to 2 days (1 day = 143 mm; 2 days = 196.8 mm; 15 days — from 22 October to 14 November — = 291.2 mm).

At the same time as the Fontelucente landslide, there occurred in Tuscany other translational slides in rock belonging to the same lithological unit (Macigno sandstone). The events related to the Piastre landslide, recorded by the Cireglio station, represent maximum annual precipitations that are above average, with variable return periods, from a minimum of 3.6 years for a precipitation of one day's duration (153 mm), to a maximum of 9 years for that of a 5-day duration (209 mm); this precipitation figure occurred in November, 1966, with 301 mm.

In February, 1951, 387 mm fell in 5 days (211 mm in 1 day; 343 mm in 2 days), which represents the maximum amount recorded for the intense events of such durations. The precipitation of 15-day duration in Fig. 2A have a return period of 7 years with 406 mm, a value surpassed only in 1959-60 with 436 mm. In examining the pluviometric data in Fig. 2B, it is observed that the landslide did not take place on the day of the greatest pluviometric intensity, but 4 days later, when an accumulation of 299 mm was recorded.

For the Marcialla landslide the events taken into consideration were those from 12 April (55.2 mm - 1day; 57.2 mm - 2 days; 65.2 mm - 3 days; 96.4 mm - 5 days), of a few days prior to the movement's collapse phase which occurred on April 25 th (Fig. 2CD).

These pluviometric events have a recurrence of less than 2 years. More indicative values turned out to be those concerning the precipitations in 15 and 30-day intervals (128.6 and 186.4 mm, respectively, with return periods of nearly 3 years). But the most important datum is that such events occurred in a spring month, at the height of the rainy season; in fact, the precipitations related to the 30-day interval of April, 1978, represent the maximum amount recorded in months from January to May (in February of 1951 alone there were 180 mm of rain).

Research into a Critical Precipitation Coefficient

As is known, the amount of water absorbed by the ground during a precipitation P is given by the relation:

$$Q_I = P - (Q_E + Q_R) \qquad (1)$$

where

Q_E = the amount of evaporated water,
Q_R = the amount of water running at the surface.

The amount of water that evaporates depends essentially on the climatic conditions and on the kind of vegetation land cover; runoff from soil permeability and topographic aspect. In similar climatic, land-cover and morphometric conditions, and taking into account events in the same period of the year, it is reasonable to consider the sum $Q_E + Q_R$ to be proportionate to precipitation P. Thus expression (1) becomes:

$$Q_I = w.P \qquad (2).$$

The rain that infiltrates and saturates the terrain's porosity forms a water table that will be recharged

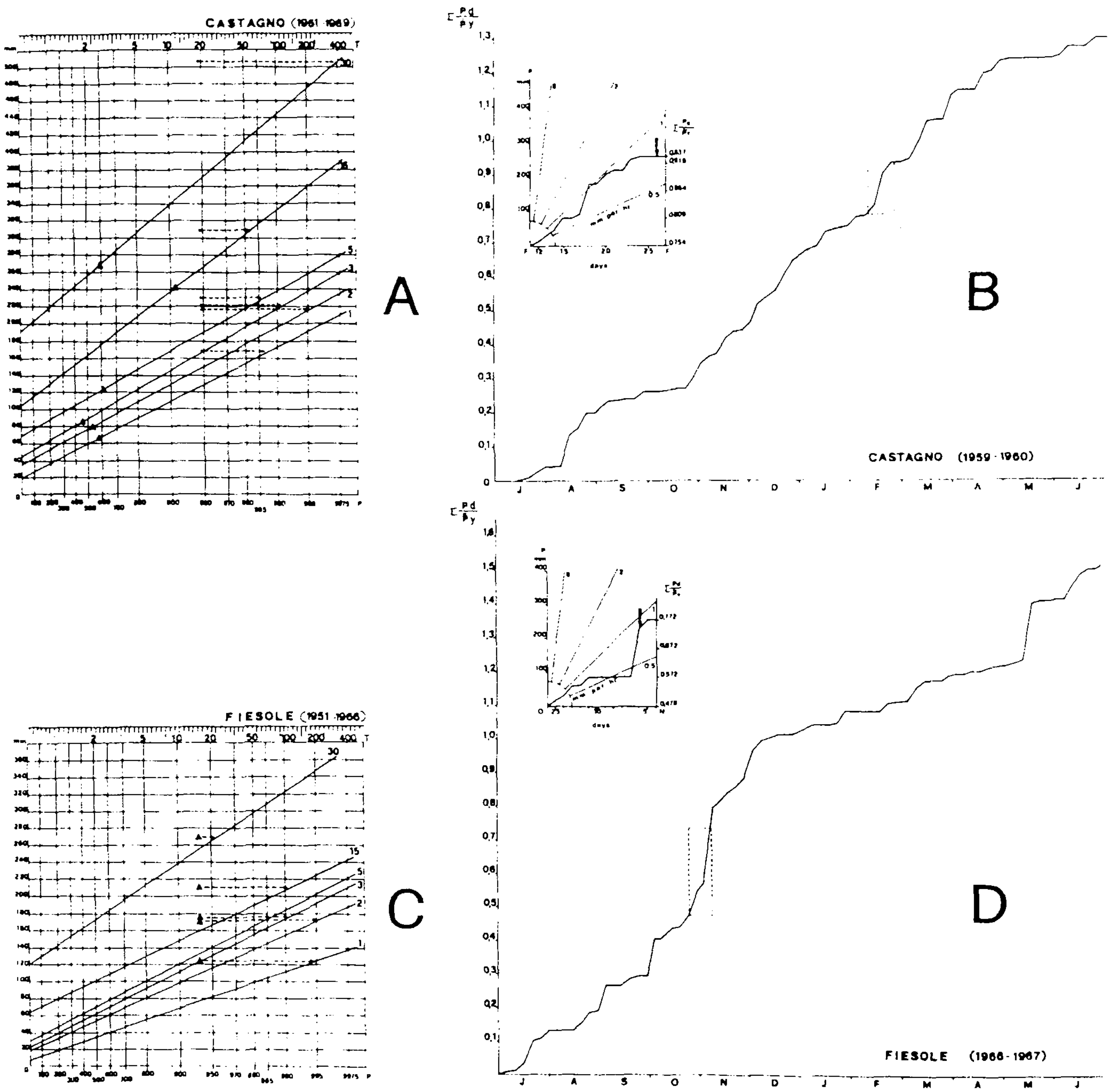

Fig. 1AC : Probabilistic diagrams of the maximum heights distribution of the annual precipitation for the duration of 1,2,3,5,15 and 30 days (station of Castagno and Fiesole). T represents the return period expressed in years. The triangles represent the precipitation events connected with the landslides, and the points the precipitations of the 4 November, 1966.

Fig. 1BD : Cumulative curves of the ratios between the summation of the values of daily precipitation, for 5-day intervals (P_d), and the yearly mean precipitation (P_y). The smaller diagrams on the left show the distribution of the daily cumulative precipitation (in mm) and the values of $\frac{Pd}{Py}$ preceding the landslide, both for one-day intervals.
The hours intensity of the pluviometric events may be estimated by the straight lines. The arrows indicate the dates of the landsliding events.

further by subsequent precipitations. The effects of a particular event will be felt for a certain period, and this is a function of the mean permeability and of the geological boundary. As regards the piezometric rise, which is the cause of a reduction in the stability coefficient, we note the importance assumed by meteoric events that are contemporary or just prior to the movement event, whereas their weight diminishes as it gets further away in time, because of the above-mentioned drainage phenomena.

The diminishing effect in time can be estimated by expressing the law with an exponential function of the type:

$$Q_l = \sum_{i=1}^{n} P_i \lambda^{n-i} \qquad (3),$$

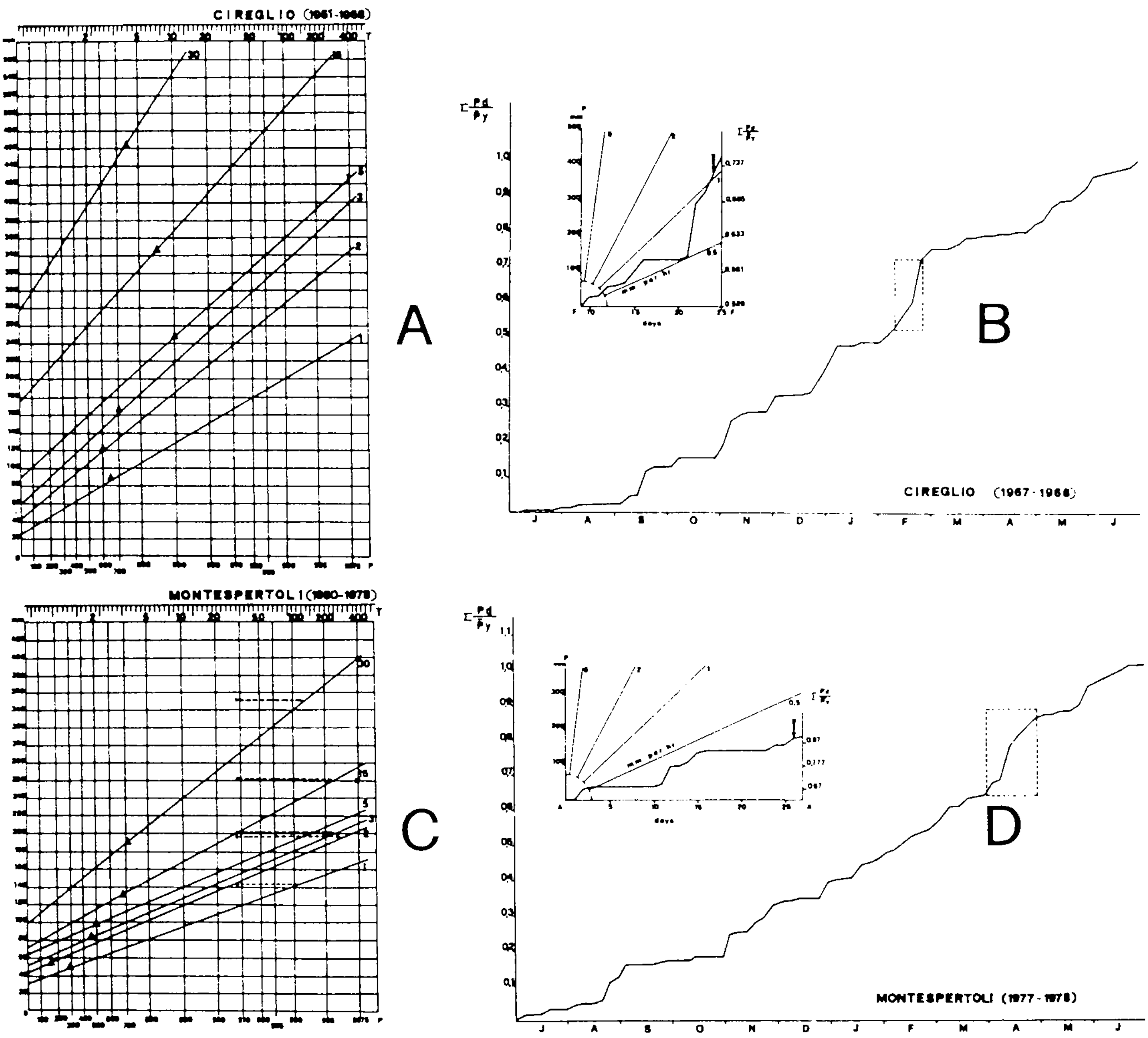

Fig. 2AC : Probabilistic diagrams of the maximum heights distribution of the annual precipitation for the duration of 1,2,3,5,15 and 30 days (station of Cireglio and Montespertoli). T represents the return period expressed in years; the triangles represent the precipitation events connected with the landslides, and the points the precipitations of the 4 November, 1966.

Fig. 2BD : Cumulative curves of the ratios between the summation of the values of daily precipitation, for 5-day intervals (P_d), and the yearly mean precipitation (Py). The smaller diagrams on the left show the distribution of the daily cumulated precipitation (in mm) and the values of $\frac{Pd}{Py}$ preceding the landslide, both for one-day intervals.
The hours intensity of the pluviometric events may be estimated by the straight lines. The arrows indicate the dates of the landsliding events.

where P_i = rainfall on the i thday; λ = the constant which regulates the phenomenon's pattern in time; n = the number of days preceding the phenomenon.

The slide capacity of an area is, of course, conditioned by exceptional events, relating the pluviometric events which provoked the slides to the area's rainfall.

Following this way, it is further possible to compare phenomena in environments with similar geomorphologic features but with different rainfall tendency.

As already stated, the coefficient expressing the degree of danger in relation to a series of daily rains may be expressed by the following relation:

$$PC \text{ (Precipitation Coefficient)} = \sum_{i=1}^{n} \frac{Pi\, \lambda^{n-i}}{PT} \qquad (4),$$

where λ depends on permeability features of the materials and increases, tending to 1, for terrains in a state of greater drainage; PT are the recurrent precipitations obtained by a statistical elaboration for different return periods. For materials of medium-high permeability like those analyzed for the study areas in Tuscany, precipitations of 15 or 30-day duration are to be considered significant.

The exceptional event can be pointed out if we consider values related to recurrence periods of 10 to 20 years. The precipitation coefficient (PC) is considered as critical (CPC) when it corresponds to precipitations that triggered the landsliding event.

Conclusions

In the four landslides being examined, the events which may have affected stability occurred in a time interval of 15 days, so that it seems justified to adopt in formula 4 a PT = 15 days and a coefficient $\lambda = 0.9$. The use of $\lambda = 0.9$ renders negligible the effects of events having occured prior to 15 days earlier.

In the following table are recorded the findings of the formula's applications, in which we consider $n = 15$, $\lambda = 0.9$ and PT as corresponding to 10 and 20 year recurrences.

	PT_{10}	PT_{20}	CPC_{10}	CPC_{20}
Fosso Falterona landslide	238 mm	266 mm	0.69	0.62
Fontelucente landslide	148 mm	169 mm	0.70	0.63
Piastre landslide	425 mm	470 mm	0.65	0.59
Marcialla landslide	238 mm	266 mm	0.48	0.43

The value of the coefficient for Fontelucente is estimated, because of lack of hourly data concerning precipitation, in the hours immediately preceding the landslide.

From the figures shown in the table, those resulting as critical have a CPC greater than 0.5 for a 10-year recurrence, and CPC greater than 0.6 for a 20-year recurrence.

For the four cases examined, which present simple geological, geomorphological and hydrogeological conditions, and which are characterized by materials of medium to high permeability, the results obtained appear interesting. We think, however, that they cannot be generalized, since for more complex hydrogeological situations there must be taken into account different values of λ.

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