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PROGRESS IN METHODS IN THE STUDIES ON SLOPE INSTABILITY IN NORTH-WESTERN TUSCANY (ITALY)

Abstract - In this paper, the course of the research on slope instability in the Serchio and Magra River valleys (north-western Tuscany, Italy) is summarized.
Research began during the '80s in the province of Pistoia, where slope instability was directly related to the characteristics of geological units. The maps produced had a particular legend explaining both geological and stability characteristics. The territory was subdivided into instability classes, substantially depending on lithologic characteristics and types of landslides. Subsequently, similar maps were drawn to evaluate the landslide hazard connected with earthquakes in a sample area of Garfagnana (mid-upper Serchio valley). More recently, slope stability maps of the most significant portions of Garfagnana and Lunigiana (Magra valley) were published. These maps were subdivided into instability classes related to geological and geomorphological characteristics of the investigated area; geological units were divided into some classes, based on the areal density of landslides.
At present, the research on slope instability is particularly aimed at determination of landslide hazard and of the recurrence time of landslides, in relation to the occurrence of triggering factors.

Key words - Slope instability, Landslide hazard, Tuscany, Italy.

Riassunto - *L'evoluzione metodologica negli studi sulla stabilità dei versanti in Toscana nord-occidentale (Italia).* In questo lavoro viene sintetizzato il progressivo sviluppo delle ricerche volte a caratterizzare la propensione al dissesto dei versanti, che ha trovato applicazione in particolare in Garfagnana e Lunigiana (valli dei F. Serchio e Magra, Toscana settentrionale).
Le ricerche iniziarono negli anni '80 nella provincia di Pistoia, dove l'instabilità dei versanti era direttamente correlata alle caratteristiche delle unità geologiche. Le carte della franosità realizzate avevano una particolare legenda, che illustrava sia le caratteritiche geologiche che quelle di stabilità.
Successivamente, furono realizzate altre carte con la stessa metodologia, allo scopo di valutare la franosità reale e potenziale connessa con i terremoti, in un'area campione della media e alta Val di Serchio.
Più recentemente, sono state realizzate carte della franosità nelle aree più significative della Garfagnana e della Lunigiana; in queste carte, il territorio è stato suddiviso in classi di stabilità, in base alle caratteristiche geologiche e geomorfologiche e all'indice di franosità areale.
Attualmente, le ricerche sono indirizzate alla quantificazione del rischio, attraverso la determinazione della pericolosità di frana e della ricorrenza temporale dei movimenti in relazione alle cause attivanti.

Parole chiave - Stabilità dei versanti, Pericolosità di frana, Toscana.

INTRODUCTION

Geological studies and research in northern Tuscany and in particular in the area of Garfagnana (Serchio River valley) and Lunigiana (Magra River valley) were initiated at the beginning of the sixties by the Institute of Geology and Paleontology of the University of Pisa, which in 1982 became part of the Department of Earth Sciences. The geological surveys that were carried out in that period led to the drawing up of Sheets 96, 97, 104 and 106 of the 1:100,000 scale Geological Map of Italy.
Since then there has been constant interest in the geological and geomorphological problems of these areas. However, this interest has been progressively directed towards increasingly specialised and applied fields.
In particular in the eighties studies were above all developed on the stability of the rocky slopes characterised by a strong argillitic and argillaceous predominance (the argillites of the Ligurian Units, the Scaglia rossa formation and the Villafranchian clays) in areas where instability had a significant impact both on built-up areas, and on man-made works of particular economic and social importance, such as power lines, roads, schools and hospitals.
The Garfagnana and Lunigiana areas are entirely located within the hydrographic basins of the R. Serchio and the R. Magra respectively. They were chosen for these studies because they are mountainous areas with a well-developed man-made infrastructure, with important towns, tourist facilities, craft industries and factories. The economic and social importance of these settlements in areas of high seismicity, often on unstable slopes of a high hazard level, wholly justifies the need to improve our knowledge in order to mitigate landslide risk.
For these reasons the latest research of the Engineering Geology Group of the Department of Earth Sciences, Pisa, is aimed at the identification of landslide hazard, by means of the determination of the return times of the landslide movements. The results expected will make it possible to plan the defence of the territory with greater effectiveness than in the past.

GEOLOGICAL CONTEXT

The northern Apennines, within which the Garfagnana

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and Lunigiana areas are situated, is unanimously considered a fold - and - thrust chain, formed during several tectogenetic phases, from the upper Cretaceous to the middle-upper Miocene. From the upper Miocene a post-paroxismal tectonics of a disjunctive type established itself, giving rise to tectonic depressions delimited by direct faults, in which lacustrine basins were formed with typically continental sedimentation.

The said geographical regions extend into these depressions, which, on the basis of findings of fossil vertebrates and pollen datings, were formed between the upper Ruscinian and the upper Villafranchian (Bertoldi, 1988; Federici, 1980; Federici and Rau, 1980; Nardi *et al.*, 1987). These two tectonic structures, stretching along the line of the Apennines, are not in longitudinal continuity, but are displaced some kilometres, because of the presence of transverse faults. The faults that identify them still show signs of activity, indicated by their morphotectonic characteristics, seismicity and the localisation of the earthquake epicentres, significantly aligned with them.

The fundamental structural model that enjoys the largest consensus for Garfagnana (Eva *et al.*, 1978; Boccaletti and Coli, 1985) and for Lunigiana (Bernini *et al.*, 1991) envisages an asymmetrical *Graben*. This structure is limited by direct faults of a listric type: in the eastern part by master faults and in the western part by high angle antithetic faults.

In Garfagnana and Lunigiana, above the metamorphic complexes, typically outcropping in the tectonic window of the Apuan Alps, there are several superimposed tectonic units, referable to Tuscan, Sub-Liguride and Liguride Domains (Fig. 1). The outcropping units are listed below, in order of geometric superimposition, from bottom to top.

Metamorphic Tuscan Sequence - It outcrops in the Apuan Alps core and is mainly composed of the Massa Unit and the Autochthon Auctt. Unit. The first outcrops almost exclusively in the western belt of the Apuan Alps, with detritic-phyllitic and quarzitic rocks. The Autochthon Auctt. more represented, includes rocks from between the Paleozoic and the Oligocene: the lower portion is represented prevalently by phyllitic and quarzitic rocks and by metavulcanites and lies under dolomitic rocks; marbles follow, with polichrome breccias; then there is a sequence represented prevalently by limestones, radiolarites, micaschists (metamorphic Scaglia rossa formation), followed by meta-sandstones (Pseudomacigno formation).

Non-metamorphic Tuscan Sequence (Tuscan Nappe Auctt.) - This unit, outcropping in its complete terms in Garfagnana and in its middle-upper terms in Lunigiana, includes: a Mesozoic portion, from the upper Trias to the lower Cretaceous, constituted by formations prevalently of a carbonatic (dolomites, limestones and marly limestones) or calcareo-siliceous type; a middle-high portion, from the Cretaceous to the Eocene - lower Oligocene (?), constituted essentially by argillites of the Scaglia rossa fm. and by limestones and calcareous torbidites interbedded in it; a summit portion, from the upper Oligocene to the lower Miocene, constituted by the torbidites of the Macigno fm., with sandstones in the basal part and sandstones and pelites in the middle-upper part.

Canetolo Unit - Outcropping in extensive areas on the roof of the Tuscan Sequence, it prevalently consists of a Paleocene-Eocene basal portion (argillites with interbedded limestones: Argille e calcari fm.), with which the calcareous torbidites of the Eocene (Calcari di Groppo del Vescovo fm.) are associated, and of a prevalently arenitic and conglomeratic upper Oligo-Miocene portion (Arenarie di Ponte Bratica fm. and Arenarie e conglomerati di Petrignacola fm.).

Ottone-S. Stefano Unit - It includes at the base the Monte Penna-Casanova Complex, of upper Cretaceous age, constituted by prevalently clastic deposits, matrix-supported (Brecce di S.Maria fm.), occasionally coarse, with large masses of ophiolites (serpentinites, gabbros, basalts) and granite. Higher up there are calcareous-marly torbidites (Flysch ad Elmintoidi di Ottone-S. Stefano fm.) with interbeddings of paraconglomerates in argillitic-siltitic matrix (Argilliti of Monte Veri fm.).

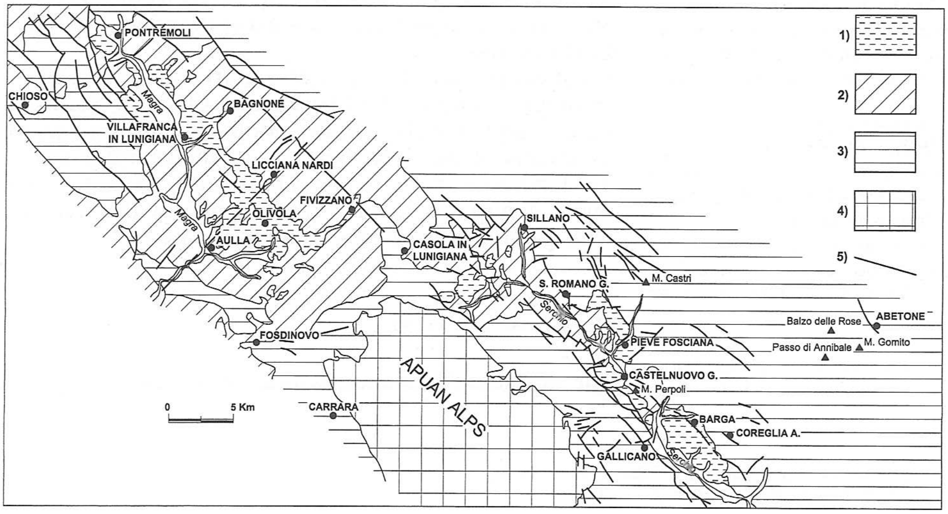

Fig. 1 - Tectonic sketch of north-western Tuscany (after D'Amato Avanzi and Puccinelli, 1997, redrawn and partially modified). 1) Fluvial and fluvial-lacustrine sequences. 2) Liguride and Sub-Liguride Units. 3) Tuscan Sequence. 4) Apuan Alps Metamorphic Complex. 5) Fault.

Lacustrine and fluvial-lacustrine deposits of Garfagnana (basins of Barga and Castelnuovo di Garfagnana) and of Lunigiana (basins of Aulla-Olivola and Pontremoli) - The sequences, referable to the Villafranchian lacustrine cycles of the Serchio valley and the Magra valley, present substantially analogous deposits. At the base, clays with vegetable remains are present with silts, sands and levels of gravels in sandy matrix; at the roof, gravels and polygenetic conglomerates, in sandy matrix, cemented in places. Such sequences are below terraced alluvial Quaternary deposits, with a prevalence of pebbles of Macigno sandstone.

GEOMORPHOLOGICAL FEATURES

The main geomorphological features of Garfagnana and Lunigiana have been determined not only by climatic conditions, but above all by lithologic-structural factors. Indeed along the slopes sub-flat or counterslope areas are still recognizable and are due to a series of steps of faults, which indicate the main tectonic reason for the morphostructural depressions.

The morphologically most depressed areas correspond to structural lows, while (still) uplifting areas correspond to the reliefs, as shown by the pronounced incisions of the torrents and by the retrogressive erosion of the valley heads.

In the most lowered parts the River Magra and the River Serchio have carved their beds, following a parallel course to the axial direction of the depressions, with a NW-SE orientation. The profiles of the two valleys are generally asymmetrical and the western slopes generally are considerably steeper than the eastern slopes. The causes are both of a lithological and structural order:

– in the two valleys the western slopes present different lithotypes from the eastern slopes; in particular, the western slopes of the Magra River valley are modelled in more coherent rocks (Flysch ad Elmintoidi fm.) than the eastern slopes, of an incoherent (sands, silts and clays of the lacustrine deposits) or pseudo-coherent nature (Monte Penna-Casanova Complex, Argille e calcari fm.); in the Serchio River valley the western slopes are generally carved into more coherent rocks (Mesozoic limestones, metamorphic rocks) than the eastern slopes (Macigno fm., Scaglia rossa fm., lacustrine deposits);

– both in Garfagnana and Lunigiana the asymmetry of the slopes is also attributable to the inclination of the faults, frequently having a listric geometry; low angle faults (master faults) are present to the west and high angle faults (antithetic faults) to the east;

– the two rivers, which, as mentioned above, flow in a NW-SE direction, in some stretches follow anti-Apennine directions: the most significant change in direction is that of the R. Serchio at Monte Perpoli, due to the Pleistocenic uplifting of the zone, which forced the river to find an alternative course, dictated by the greater erodability of the rocks affected by faults and cleavage (Puccinelli, 1987). Other Pleistocene tectonic uplifts and tilting have involved the zone further downstream, at Barga (D'Amato Avanzi and Puccinelli, 1989b). The R. Magra also shows a sharp deviation at Aulla, assuming an anti-Apennine course, which follows a transverse tectonic line, referable to a left transcurrent fault (Raggi, 1988; D'Amato Avanzi and Puccinelli, 1989a).

MASS MOVEMENTS

In the two regions mass movements play a very important role in morphogenesis; these include landslides, according to the usual definition of the term, and Deep-seated Gravitational Slope Deformations (DGSD). The latter present some peculiarities with respect to the common landslides, which justify their being treated separately from landslides; the DGSD will be described later.

Landslides

Landslides occur in all the lithological types outcropping in the basins considered; however, some formations show a considerably greater spread of movements and characteristic types of movement. Summarising the relationships between the lithotypes and landslide typologies (Varnes, 1978; Carrara, *et al.*, 1987; Cruden and Varnes, 1996) it can be stated that:

– the argillitic and argillaceous rocks (Argille e calcari, Brecce di S. Maria and Scaglia rossa fms., pelitic deposits of the lacustrine series) are very commonly subject to landslide, with frequent phenomena of rotational slide, flow and slide-flow;

– in the most competent rocks (limestones of the Mesozoic series of the Tuscan Sequence, Macigno, Flysch ad Elmintoidi and Calcari di Groppo del Vescovo fms.) landslides are less frequent and are represented in particular by falls and translational or, less frequently, rotational slides, where the rock masses are very fractured;

– in the debris covers, extending over large areas at the foot of the slopes in coherent rocks or at the foot of fault escarpments, there is a prevalence of translational slide phenomena on the bedrock and of rotational slide, flow or slide-flow; also widespread are phenomena of solifluxion, while debris flows are frequent in particular morphological and rainy conditions.

The slope instability is linked not only to the already described lithologic-structural factors, but also to the meteo-climatic conditions and to the high level of seismicity.

The rainfall values are typical of the internal Apennine zones with annual averages, on a thirty-year basis, around 1,500-2,000 mm/year in the central zones of the tectonic depressions; near the culminations of the Apuan Alps and the Tuscan-emilian Apennines rainfall exceeds 3,000 mm/year (CNR, 1964; Baldacci *et al.*, 1993).

Fairly frequent (every ca. 5 years) are the episodes in which the precipitations are concentrated in extremely brief time intervals, causing rapid increases in discharge and in solid transport and giving rise to a large

number of debris flows (Nardi *et al.*, 1987; Caredio *et al.*, 1998; D'Amato Avanzi, 1999; D'Amato Avanzi *et al.*, 2000): in August 1987 in upper Garfagnana there was a rainfall of 100 mm in about 3 hours; on 19th June, 1996 in the area between Garfagnana and Versilia, almost 500 mm in 12 hours were recorded, with an hourly intensity of up to 158 mm/hour.
It should finally be remembered that Garfagnana and Lunigiana are among the most seismically active areas of the northern Apennines; frequent earthquakes have been recorded often with high magnitudes (Postpischl, 1985; Boschi *et al.*, 1995), often with epicentres aligned along the faults which characterise the above mentioned depressions; in particular, the 7th September, 1920 earthquake (Patacca *et al.*, 1986) was a severe ordeal for the inhabitants of the two regions, reaching an intensity of the X degree MCS. That earthquake led to the remobilisation of the great landslide of Caprignana Vecchia (upper Serchio valley), which involved the village of the same name, subsequently rebuilt in a position also exposed to landslide hazard.

Deep-seated gravitational slope deformations (DGSD)

DGSD are mass movements, characterised by considerably large dimensions and particular modes of evolution, in which it is generally not possible to recognise a continuous, well-defined slip surface, substituted at depth by a rocky thickness involved in phenomena of visco-plastic deformation. These phenomena are the object of broad scientific research (see for example Zischinsky, 1969; Mahr and Nemcok, 1977; Radbruch-Hall, 1978; Bisci *et al.*, 1996), which in several cases underlined some uncertainty in the distinction between landslides and DGSD, which might not be exempt from subjective interpretations. Referring to the classifications of Varnes (1978), Carrara *et al.* (1987) and Cruden and Varnes (1996), the DGSD are essentially comprised within the phenomena of rock spread, rock flow and complex type. Hutchinson (1988) regards as «sagging of mountain slopes» those movements that «in their present state of development, do not justify classification as landslides».
DGSD play a very important role in the evolution of slopes and are often the cause or contributing cause of more superficial phenomena of instability. They are situated in an intermediate position between large landslides and structures connected with the gravitational tectonics. In the regions studied the conditions commonly considered favourable to their occurrence have been found:
– high relief energy, with steep slopes, well developed in height and modelled in competent rocks;
– meteo-climatic conditions favourable to particularly active canalized erosion, with high rainfall values;
– high level of seismicity;
– active or recently active tectonics.
The studies undertaken (D'Amato Avanzi and Puccinelli, 1989a; Dallan *et al.*, 1991; D'Amato Avanzi *et al.*, 1995a, 1997; D'Amato Avanzi and Puccinelli, 1997; Baldacci *et al.*, 1997; Buti *et al.*, 1997; Caredio *et al.*, 1997) made it possible to recognise that in the DGSD examined a primary role is played by structural features and lithostratigraphic structure, which condition their typological and kinematic characteristics. The climatic conditions and the neotectonic evolution, on the other hand, have a more widespread areal rather than localised effect.
The direct faults and cleavage have exercised on the rocky masses an action of detachment and fragmentation into megablocks, making possible their gravitative adaptation; moreover, the arrangement of the fundamental morphological features (in particular counterslopes and «trenches») in accordance with systems of brittle deformation can be observed. In particular, reference is being made to the DGSD at Villafranca in Lunigiana, Bagnone and Podenzana (province of Massa-Carrara), San Romano in Garfagnana (province of Lucca) and Abetone (province of Pistoia). Such movements can be considered block slide/spread phenomena and occur along the fault zones.
Somewhere else, the lithostratigraphic structure greatly conditions the DGSD. In particular, the most favourable structure is given by rigid rocks on ductile rocks, favouring typologies such as block slide and spread, as was verified in the Serchio valley (M. Castri and Abetone) and in the Magra valley (zones of Bagnone and Rocchetta di Vara).
The assessment of the state of activity of the DGSD has often been difficult, because in most cases they have the character of intermittent movements: dormancy or imperceptible movement periods probably alternate with paroxysmal phases, due to seismic events or to climatic crises.

STUDIES ON SLOPE INSTABILITY

The basis of the current research in Garfagnana and Lunigiana are the studies carried out in the entire territory of the province of Pistoia at the beginning of the 1980s. The slope instability was related to the lithological characteristics of the formations outcropping in the territory studied (Nardi *et al.*, 1981).
Subsequently, the Slope stability map of the Serchio valley between Pieve Fosciana and Camporgiano, on a scale of 1:10,000 (Nardi *et al.*, 1986a), was produced in order to assess landslide hazard induced in a seismic area (Earthquake project in Garfagnana and Lunigiana; CNR - Regione Toscana, 1986). This map, while presenting some innovative elements with respect to that of the province of Pistoia, was conceived substantially with the same criteria, consisted of a single map, complete with a double legend. One was of the classical, geological type, while in the other the rocks corresponding to the lithostratigraphic units were assessed with numbers expressing different values of the tendency to landslide of each formation.
These studies constituted one of the first results of a broad programme of research on slope instability in Garfagnana (CNR - GNDT: Prediction and prevention of the effects of earthquakes on the stability of natural slopes) and Lunigiana (CNR - GNDT: Elaboration and surveys on the tendency to landslides in areas of particular seismic interest: Lunigiana; Ministry of Education – 40%: Slope insta-

bility and methods of intervention and Geological and geotechnical characterisation of sample landslides in central-northern Tuscany).
The results obtained (Nardi *et al.*, 1986a, 1986b, 1987, 1989, 1990, 1993; D'Amato Avanzi and Puccinelli, 1988; Dallan *et al.*, 1991; D'Amato Avanzi *et al.*, 1991) made it possible to develop a method that established, by means of lithological and geomorphological factors, some parameters for the recognition and classification of the areas of landslide, of those potentially subject to landslide, of those of medium stability or stable (Fig. 2).
The research carried out has found and confirmed the concentration of landslide phenomena within the argillitic or argillaceous formations, referable above all to the Scaglia rossa fm., to the base complexes of Sub-Liguride and Liguride Units and to the lacustrine and fluvial-lacustrine deposits.
The data that emerged, concerning the surface disrupted, the formation involved and the most important causes, were processed statistically, with the aim of obtaining for every formation an index of landslide density (surface of landslides in that formation divided by its total outrop surface). The value of this index made it possible to subdivide the formations into classes of lithological hazard, always in the sense of a tendency to landslide. In practice, the surface undergoing landslide is related to the outcropping surface (chosen so that it is statistically significant for the formation being examined), without local morphological influences favourable (terraces, flat areas) or unfavourable (bank erosions, etc.) to stability. In this phase of assessment, the accumulations of landslides are attributed to the formation from which they derive. The detritic covers are, on the other hand, considered apart, maybe constituting a parameter relative to the degradability of the formation and to the genesis of debris flows. The classes used are relative to the following intervals in the value of the index of landslide density (LD) and are distinguished on the map by a reference colour (Fig. 2):

$0 < LD < 0{,}1$ $0.1 < LD < 0.2$ $0.2 < LD < 0.3$ $LD > 0.3$

The results thus obtained make it possible to distinguish areas of different tendency to landslide, as well as those already involved in either active or dormant landslides.
As a final result, a large number of thematic maps have been produced. Their aim is to characterise the stability of the territory. An applied geological and geomorphological picture of the middle and upper Serchio River valley and of vast significant areas of the Magra River valley was thus obtained, surveyed and interpreted homogeneously. The information derived from this are of a prevalently descriptive type, and describe the present geomorphological phenomena; they fulfils the need to provide a product, that combines scientific rigour with clarity of exposition, thus facilitating its use in territorial planning, also by non-specialised personnel. Therefore, the representation adopted does not consider some quantitative aspects of slope stability. Furthermore, the definition of landslide activity is based above all on the data that is objectively observable on the ground during the survey and does not take into account possible periodicity or recurrence of dormant movements. Such a method proved to be very reliable and was also used in the production of the Slope stability map of the Serchio River Basin, on scale of 1:10,000 (Nardi *et al.*, 2000), which with 13 sheets covers the most significant areas of Garfagnana and Middle Serchio valley.
Following the catastrophe in Versilia of 19th June, 1996, studies were carried out on geological, geomorphological and climatic factors in the activation of hundreds of rapid debris slide - debris flows, which caused 14 deaths and extensive damage to towns and villages, infrastructures and productive activities (Caredio *et al.*, 1998; D'Amato Avanzi, 1999). In particular, quantitative studies carried out on about 400 landslides in the worst hit basins, where up to 70 landslides/km^2 occurred (D'Amato Avanzi *et al.*, 2000), pointed to some factors that most influenced the localisation and characteristics of the landslides. In particular, the lithological constitution of the bedrock proved to be of primary importance, represented in most of the cases analysed by meta-sandstones and phyllites, impermeable and often affected by significant discontinuity

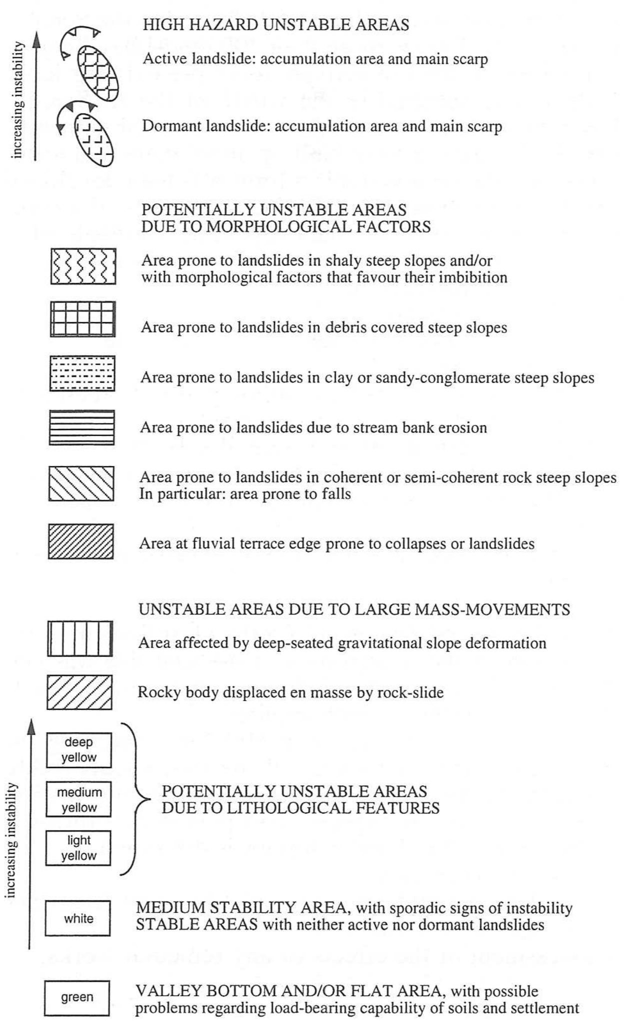

Fig. 2 - Legend for the slope stability maps of Garfagnana and Lunigiana.

dipping downslope. The distribution of the landslides in relation to morphology showed a fairly typical configuration of the slopes in the areas of detachment, with rectilinear profile and hollow form, with a fairly high inclination (generally between 30° and 45°). This study made it possible therefore to identify the fundamental characteristics of the areas most subject to slide and to zone potential instability. The research is still in progress and examines other parameters (geotechnical, hydrogeological and climatic) in order to further refine and perfect the model.
Finally, we also mention some studies on slope instability in north-western Tuscany and eastern Liguria (by other authors of the Department of Earth Sciences, Pisa).
As regards Lunigiana, Baldacci and Raggi (1969) produced a small scale slope stability map of the Magra River basin (1:100,000 scale, mainly oriented to a regional assessment of disruption). In this map, landslides and landslide-prone areas were mapped, and slope instability was classified into four categories, principally related to lithologic characteristics. More recently, Baldacci *et al.* (1994-1995) produced a slope stability map (1:5,000 scale) in a small test area of the lower Magra valley. In this map, slope stability was mainly linked to lithotechnical characteristics, although slope steepness and strata-slope relationships were also considered. In addition, locally geomorphic, hydrologic and structural factors were considered.
Regarding the Serchio River basin, Noti (1998) produced a 1:10,000 scale map of potenzial slope stability of a small test area between Mt. Prato Fiorito and Alpe delle Tre Potenze, not far from the main Apenninic watershed. The author applied a conditional analysis technique, based on statistical relations between some geo-environmental factors and the occurrence of landslides. Lithology, strata-slope relationships, slope steepness and length, relative position on slopes and soil use were considered. Therefore, the area was subdivided into five instability classes.

STUDIES ON HAZARD

The approach described above makes it therefore possible to obtain a comprehensive picture of the instability of a particular territorial context, to achieve a better management of the physical environment, above all in relation to the man-made environment. However, the importance of the availability of more data regarding landslide hazard, in the sense of the probability that a landslide event with certain characteristics will occur in a given area within a given time interval, became evident. It became therefore a prime necessity to assign a large part of resources to this sector of research.
The research project on landslide risk, which envisaged a survey of landslide hazard in the whole of the territory of Garfagnana and Lunigiana, proved to be extremely difficult as regards the finding of evidence, reliable documents and reports on landslides, necessary to establish the recurrence of their movement. The studies concentrated above all on more limited areas of the Serchio River valley; in particular, landslide hazard was defined in highly critical areas, like that between S. Romano in Garfagnana and Pontecosi (D'Amato Avanzi *et al.*, 1995). At the conclusion of the applied geological and geomorphological surveys and of the historic-archive research, above all in relation to the re-activation of landslides induced by earthquakes, by rainfalls and by man, it was possible to identify the numerous recurrent movements, even on an annual basis. Four classes were therefore distinguished (following the guiding principles of the method proposed by Del Prete *et al.*, 1992) with different gradations of hazard based on return time (RT), expressed in years:

Class	I	(Low hazard level)	RT >50	Intermittent landslides
Class	II	(Medium hazard level)	10<RT<50	Intermittent landslides
Class	III	(High hazard level)	2<RT<10	Intermittent landslides
Class	IV	(very high hazard level)	RT<2	Continuous or seasonal landslides

In collaboration with the Serchio River Basin Authority, in the context of the definition of the basin plan, there has been a further development in the studies on the assessment of landslide hazard in the Serchio River valley. Firstly, more than 200 landslides (in general partial or total re-activations of pre-existing landslides) were selected in the whole of the R. Serchio basin: these determine situations of particular vulnerability, in that they involve built-up areas, dams and reservoirs, and the road system. A form was then developed for the acquisition and archiving (by means of a computer data-base) of the data regarding landslide phenomena. In particular, the essential information collected and catalogued are:
- geological structure;
- typology and morphometry of the landslide;
- rate of movement;
- existence of geological and/or geologic-technical studies and geognostic investigations;
- known re-activations and state of activity;
- causes of the landslide and/or of any re-activations;
- facilities involved and damage produced by the landslide;
- remedial works planned and/or realized and effects obtained.

The collection of data useful for the identification of the periodicity of the re-activation of the landslide was performed, according to the method illustrated by D'Amato Avanzi *et al.* (1996), which requires:
- collection of information useful for identifying the localization and chronology of the movements (bibliography, historic-archival research at public institutions, libraries, newspaper and periodical libraries, archives of cultural and religious institutions);
- comparison of data;
- supplements and revisions of data, geological and geomorphological surveys;
- assessment of the effects of any remedial works;
- assessment and gradation in classes of the hazard for every landslide, on the basis of its return time.

Such hazard combines all the contributions to hazard due to earthquakes, rainfalls, erosive actions and anthro-

pogenic interventions; a programme of studies has therefore been initiated, the aim of which is to identify the connections between these causal factors and the landslides. Experimentation has in any case shown the actual state of risk of the areas studied. It is significant that 75% of the landslide movements studied proved to be of a high or very high level of hazard (D'Amato Avanzi *et al.*, 1999). Even if in many cases the rate of movement is not such as to threaten human life, considerable damage is predictable. The need was therefore confirmed to broaden the research, at least on the landslides of greater hazard and to make safe slopes on which built-up areas are located: their stability is at present unpredictable, above all in seismic conditions, in areas where the intensities of the predicted earthquakes reach the X degree MCS (Cattaneo *et al.*, 1986).
Studies on landslide hazard, aimed in particular at determining the return times of the critical landslide-triggering rainfall thresholds, were also carried out in the area between Versilia and Garfagnana, devastated by debris flows and flooding phenomena in the catastrophe of 1996, recalled above. The statistical processing of pluviometric data, on the basis of estimated and documented thresholds, has provided a return time (for precipitation with analogous characteristics to those of 19th June, 1996) which for some rainfall recording stations is just over a hundred years (Caredio *et al.*, 1998). Such a value, confirmed also by some unpublished historical research, emphasises the serious state of risk of these basins. This research is also continuing both with historical inquiry into past phenomena and with further study of aspects relating to the critical threshold for triggering landslides. The aim is thus to characterize further the hazard of the area and provide more precise data in the setting up of risk scenarios and prevention and mitigation measures, also in adjacent basins, where the conditions of risk are in many respects similar.

CONCLUSIONS

The degree of refinement of the studies on slope instability in Garfagnana and Lunigiana makes it possible, finally, to make some considerations on the methods previously used.
In the first maps (the Geological and geomorphological map of the province of Pistoia and the Slope stability map of the Serchio River valley between Pieve Fosciana and Camporgiano), the problem of representing the geological formation and its characteristics of landslide hazard was solved with a single map, complete with a double legend which showed the two parameters separately. Thus, synthesising documents were produced that were valid in terms of content, but perhaps not immediately legible, above all by non-specialist users: the geological part was graphically preponderant and the assessment of the global hazard of an area made it necessary to consult the two legends frequently.
The maps produced for the CNR - GNDT in Garfagnana and subsequently in Lunigiana constituted considerable progress, in that the tendency to landslide of the various lithotypes was classified on a statistical basis, with the aid of the geological and geomorphological study of the areas.
These studies have led to the production of a large number of thematic maps whose aim was the characterisation of the stability of the territory. The information derived from them are of prevalently descriptive type, describing of the geomorphological phenomena present. The representation that is made of them defines precisely the state of the areas at the moment they are surveyed and characterises the areal context in which the landslide phenomena develop. It is not however exhaustive enough for more effective territorial planning, for which a more precise quantification of risk would be necessary.
The studies currently in progress on landslide hazard aim to achieve this, by determining, through the identification of the relationships between the landslide movements and the recurrence of the landslide - triggering events, the probability of occurrence of a landslide movement of given characteristics.
Such studies are part of research programmes in progress, but are also associated with the production in the near future, promoted by the Italian National Geological Survey, of an experimental sheet (Sheet 250 - Castelnuovo di Garfagnana) on the theme Geological hazard linked to slope instability.
The results aimed at are in particular the spatial and temporal prediction of possible catastrophic phenomena. The assessment of the degree of hazard of a slope will be performed through the study of the main factors (geologic-structural, geomorphological, lithotechnical, pluviometric, hydrogeological, seismic, man-made, etc.) that predispose to and determine instability. In particular, through the analysis of the distribution and of the spatial relations of landslides and factors of instability, the end result will be the identification of the degree of tendency to landslide and potential slope instability of the territory. The high number of variables requires an approach that uses multi-varied statistical techniques and Geographical Information Systems (GIS), at present in an experimental phase in sample areas of the Serchio River valley. Moreover, the probability of occurrence will also be assessed, both through historical analysis, and the study of temporal series of triggering causes (rain, earthquakes, erosive actions).
This will make it possible to identify the areas of highest risk and therefore, in the management of the territory, to programme interventions and to direct resources to situations that present the most critical conditions, so as to provide effective prevention and mitigation of risk.

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