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LANDSLIDE, SPREADING, DEEP SEATED GRAVITATIONAL DEFORMATION: ANALYSIS, EXAMPLES, PROBLEMS AND PROPOSALS

ABSTRACT: CROSTA G., *Landslide, spreading, deep seated gravitational deformation: analysis, examples, problems and proposals* (IT ISSN 0391-9838, 1996).

Technical literature about deep seated gravitational deformations is becoming more and more copious. Anyway, it is still evident the difficulty in finding a correct and complete definition for such phenomena. This paper put in evidence the main features, problems, behavioural models and improvements starting from the existing specific literature and showing some difficulty, triviality and misunderstanding. Nomenclature problems, characteristic features, differences in describing the same or similar phenomena, phenomenological and mechanical models are summarised on the basis of more than 400 titles concerning such a theme.

Eventually, few suggestions are proposed on the basis of field observations, geomechanics knowledge and mechanics principles. Simple statistical analyses of existing data have been used to identify major features, geometries and boundary conditions to be introduced in simple numerical modellings performed by finite differences techniques. Some interesting initial results are compared with case histories taken from the literature, evidencing particular deformational patterns and identifying deep seated gravitational deformation prone settings.

KEY WORDS: Deep seated gravitational deformation, Classification, Numerical modelling.

RIASSUNTO: CROSTA G., *Frane, espandimenti, DSGD: analisi, esempi, problemi e proposte* (IT ISSN 0391-9838, 1996).

Le deformazioni gravitative profonde di versante sono un argomento di cui la letteratura tecnica si è spesso occupata producendo così un ragguardevole numero di pubblicazioni. Nonostante tale impegno persistono ancora molte difficoltà nella definizione di tali fenomeni per poterli distinguere da comuni processi di franamento. Il presente lavoro tenta di evidenziare i caratteri fondamentali, i problemi più frequentemente citati e i modelli di comportamento proposti in letteratura. Tali problemi nomenclaturali, i caratteri più tipici, le differenze da fenomeni simili, i modelli meccanici e fenomenologici sono riassunti a partire dalla revisione di una vasta raccolta di circa 400 articoli sull'argomento. I titoli impiegati sono inoltre resi disponibili al pubblico tramite Internet. Alcuni suggerimenti sono proposti sulla base di osservazioni di campagna, su conoscenze e principi di geomeccanica. L'impiego di semplici metodi statistici ha inoltre consentito di identificare i caratteri geologici, morfologici, geometrici e le condizioni al contorno più frequenti, tali da consentire l'impostazione di alcune semplici modellazioni numeriche in parte sviluppate e qui presentate e in parte ancora da sviluppare. In questo modo si sono ottenuti alcuni risultati iniziali che possono essere confrontati con quanto descritto a riguardo di casi specifici, mettendo inoltre in evidenza i pattern deformativi più tipici e l'associazione di condizioni più favorevoli alla formazione di deformazioni gravitative profonde di versante.

TERMINI CHIAVE: Deformazioni gravitative profonde, Classificazione, Modellazione numerica.

INTRODUCTION

Deep seated gravitational deformation is a definition that has acquired more and more importance in these last decades as suggested by the always abounding technical papers related to such a problem. As a consequence of this fervent activity a large number of examples has been produced from different locations, with different definitions and with dissimilar invoked mechanisms and evolutionary models. For each important mountain belt exists at least one example of deep seated gravitational deformation, linking these phenomena to any high relief environment with different rock mass lithology and geomechanical characteristics.

Anyway, it doesn't exist yet a correct and complete terminology and especially a definition for these instability processes. Geometrical, morphological and mechanical definitions have been proposed, but without any clear differentiation from what it is generally call a landslide.

As a consequence, different steps are retained necessary for a better comprehension of the phenomena. Reference listing and bibliographical review aimed to the individuation of main geometric, morphologic and geomechanical features are the main expectation of a research which want to study these phenomena improving their modelling. At the same time, it seems more correct to list and describe phenomena and the proposed mechanisms before to list the different definitions to clearly perceive in what definition are close or far from their correct classification.

Reviewing the available technical literature has been the first step of this research. Aim of such a review was the collection of examples of deep seated gravitational deformations, the implementation of a complete analysis com-

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prehensive of geographical, geomorphological and structural settings and a better understanding of the existing knowledge regarding deep seated gravitational deformations. This understanding is retained as a primary need to define the phenomenon, diversify it from other slope movements, discuss existing definitions and models suggesting changes or complementary observations. What is reported in the following must be interpreted as an attempt of the authors to summarize the major findings without any presumptuousity, quoting only the papers resulted more useful for the understanding of the processes. References, in this paper, will be limited to the more general or fundamental ones and any important omission must be excused.

As a secondary result, to be mentioned just because of the public utility, more than 400 titles have been collected in a reference list that will be maintained updated in the future. This list is available on Internet thanks to the help of Consiglio Nazionale delle Ricerche - Istituto Ricerche per la Protez. Idrogeologica (Perugia) in the Gruppo Nazionale Difesa Catastrofi Idrogeologiche Home Page (http:\Cnr.Irpi.Unipg.It).

The list has been assembled starting from previous reference lists (PASUTO & SOLDATI, 1990) with the original papers by the austrian authors, through some of the main international conferences (1977) up to the more recent italian workshops and other papers on international journals. Both for a definite choice of the compilers and for the presence of papers treating of different phenomena within this conferences and workshops, the reference list includes papers not only concerning deep seated gravitational deformation, but also creep phenomena and creep mechanisms, large landslides, lateral spreadings, toppling instabilities, gravity tectonics, theoretical stress distribution, monitoring and modelling.

REVIEW AND DISCUSSION OF LITERATURE

Subjects and years of publication

A first subdivision among these papers have been tried starting from the main treated subjects (large landslides, deep seated gravitational deformations, etc.) and are summarised in figure 1a, where according to the importance and extension of the treated arguments the same pubblication could be placed in more than one class. Again, different interest about this problem is evidenced by an histogram showing provenance from different countries (fig. 1b), while geographical distribution is summarized in figure 1c and 1d.

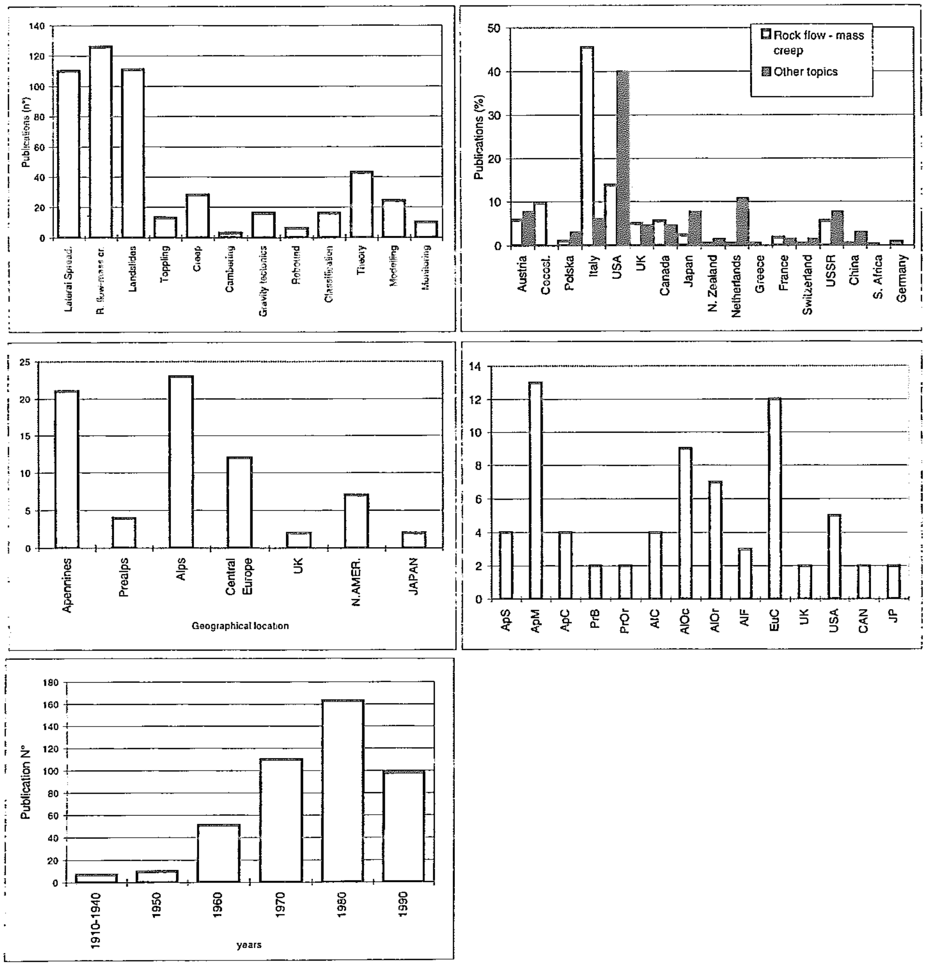


FIG. 1 - Histograms for a) main subject, b) country, c) general and d) detailed geographical location, e) year of publication for papers taken from specific technical literature. Number of publication is placed on the y axis.

One more piece of information is the year of pubblication for each quoted reference. It is clear from the histogram of figure 1e, the strong increment in the number of publications starting from the 1970. The first interval going from 1910 to 1940 includes the initial papers from the austrian school (STINI, 1941, 1952) concerned about double ridges and large landslides. During the fifties (1950) some authors start talking about creep in slope instability processes and we also observe the first appearance of gravity tectonics theory (VAN BEMMELEN, 1950). Gravity tectonics remains one of the leading arguments during the sixties with the work by ENGELEN (1963) together with some of the more important papers on deep seated gravitational deformations (JAHN, 1964; ZISCHINSKY, 1966, 1969a, b, c; BECK, 1968; MENCL, 1968; NEMCOK, 1966), lateral spreading and block sliding (NEMCOK & PASEK, 1969, NEMCOK & RYBAR, 1968; PASEK, 1968; ZARUBA, 1969, ZARUBA & MENCL, 1969, 1976), creep (HAEFELI, 1965; TER STEPANIAN, 1966), influence of stress release and glacial pressure on slope instability (FERGUSON, 1967; KNILL, 1968).

The 1970s peak coincides with an international effort for a better understanding of the phenomena. The proceedings of the International Iaeg Conference hold in Prague (1977) are among the main results of this decade together with some major papers by TABOR (1971), NEMCOK (1972), MAHR & NEMCOK (1977), RADBRUCH HALL ET AL. (1976, 1977, 1978), some of the very first modelling studies (KOSTAK, 1977, EMERY, 1978), and some classifications (ZARUBA & MENCL, 1976; VARNES, 1978). In the same decade, the italian researchers started their production on the argument; this production continued through the following years sustained by an informal scientific group gathering researchers with different interests (geomorphology, engineering geology, structural geology).

Geomorphological, geological and geomechanical descriptions were the main concerns in the following decade. A large amount of examples have been reported, both for deep seated gravitational deformations and lateral spreadings, from all over the world (BOVIS, 1982, 1989; VARNES & *alii*, 1989) with a strikingly abundance from Italy (CANCELLI, 1980; FORCELLA, 1984; MORTARA & SORZANA, 1984; CANCELLI & PELLEGRINI, 1987; FORCELLA & ROSSI, 1987; GUERRICCHIO & *alii*, 1986, 1987; CARDINALI & *alii*, 1989; RAMASCO & *alii*, 1989; CANUTI & *alii*, 1989; just to mention few of them). Nevertheless, slides and large landslides are frequently found among the subjects of these papers without real connection with deep seated phenomena. Classifications and some theoretical studies have to be mentioned together with some of the rarest monitoring surveyings. HUTCHINSON (1988) presented a general slope movement classification with a part specifically dedicated to deep seated gravitational deformations. The phenomena have been described according to main surface daylighting location with respect to the ridge (before or behind the main hill crest), to the geometry of movement surface (circular, listric, biplanar) and symmetry (symmetric and asymmetric); furthermore, scarps have been described as normal downslope down movement facing, up slope downhill facing and as upslope up movement facing. Theoretical studies include the influence of topography on stress distribution and concentration near ridges and valleys (MCTIGUE & MEI, 1981; SWOLF & SAVAGE, 1986; AMADEI & *alii*, 1987, 1988) according to closed analytical solutions implemented from elasticity theory. Monitoring of large deep seated phenomena is the basis, as introduced by BOVIS (1982, 1989), for the reconstruction of movement characteristics and potential movement surface location. Eventually, VOIGHT (1988, 1989) suggests a method for movement and time of failure prediction on the basis of monitoring results and beginning from previous works by SAITO (1969) and FUKUZONO (1984).

In the first part of this last decade, we still observe an increase in the number of publications with continuous reporting of examples and some more theoretical and numerical analyses. CHIGIRA (1992) presented an enlightening study on rock mass creep phenomena, of different scale, describing the existing features as cataclastic bands, shear zones, buckling folds. Toppling development is reintroduced with renewed vigour to explain some major slope instability phenomena (PRITCHARD & SAVIGNY, 1991; AYDAN & *alii*, 1992) also reinterpreting old proposed models such as the flexure formation proposed by ZISCHINSKY (1966, 1969a, b, c) and other authors (FURLINGER, 1972; HOFMANN, 1973).

Theoretical studies have gone farther exploring the effect of anisotropy on stress distribution and concentration (AMADEI & PAN, 1992; PAN & *alii*, 1994, 1995; SAVAGE, 1993, 1994) by means of closed solutions. Numerical modelling took a substantial step by introduction of new more specific softwares for geomechanical simulations. Most of such a modelling mainly concerned lateral spreading (CASAGLI, 1993) and few other processes (toppling: PRITCHARD & SAVIGNY, 1991; deep seated gravitational instabilities: CROSTA & BERTO, 1996).

HUTCHINSON (1995) accomplished one more classificational effort by suggesting some geometrical parameters and their limits as boundaries between deep seated slides and landslides of intermediate thickness, as well for a better shape description.

A collection of examples, descriptions, major features, definitions and classifications has been the main heritage from this long revising job. In the following, such an heritage will be presented and discussed and partially adopted in performing parametric studies by means of numerical modelling techniques.

Discussion of the processes as presented in literature

A phenomenological and mechanical description of the process is probably among the most important aims of a study on slope instabilities and especially on deep seated gravitational deformations. Main features observed on the field have been usually interpreted as representative of these phenomena and to some of them has been attributed a specific mechanical meaning. At the same time, different researchers gave different significances to these features placed along the slope profile. In the following it will be given major attention to describe mainly sackung-type phenomena because of the recent publication of quite complete works about lateral spreading (CASAGLI, 1993; CANCELLI & CASAGLI, 1995). In the following lateral spreading data will be quoted and presented only where useful to put in evidence differences with sackung-type phenomena.

Trenches, scarps, grabens, double ridges, up-hill facing scarps are the more frequently described features in the upper slope sectors. Counterscarps, up-hill facing scarps are the main intermediate slope features, while bulging, scree slopes and buckling folds or highly fractured rock masses compare at the slope toe. Superimposed and connected to such phenomena are minor slope instabilities like toppling, falls both at the top and at the toe of the slope.

A flexural structure of the slope is a frequently described feature since the first studies on sackungen (saggings) by ZISCHINSKY (1966, 1969) and NEMCOK (1972). In fact, in these classics of sagging literature, the Raztoka (Tatras Mts.) (fig. 2a) and the Matrai-Glunzerberg (fig. 2b) show the geometrical relationships, the importance and pervasiveness of flexures deriving from gravitational deformations. The two examples start from different dipping conditions, with obsequent and consequent slopes, finally evolving to relatively similar structures. The Raztoka ridge combines upper slope scarps with foliation flexuring and bulging toe; the Matrei slope starts with highly dipping foliation planes to reach a final flexure assemblage by two shearing zones, so called because of no discontinuity plane formation. The same final structure, as it will be shown later, could be reached by displacement of the upper sector and partial dragging of the underlaying rock mass material.

Two more examples help in the discussion about deep seated instabilities. The same problem, initially described by NEMCOK (1972) (fig. 3a) through simple sketching of scarps, up-hill facing scarps has been revised by MAHR (1977) (fig. 3b) who tried a much deeper reading and extrapolation of the surficial structures. Mahr makes use of the contractant theory for creep to motivate the change in volume of the central sliding mass sector respecting the mass balance. Nevertheless, brittle creep is generally recognised as a dilatant process, developing through the formation of microcracks and then with an increase in volume and a possible volume reduction only for subsequent shear. On the contrary, ductile contractant creep needs very high stresses or temperature to evolve.

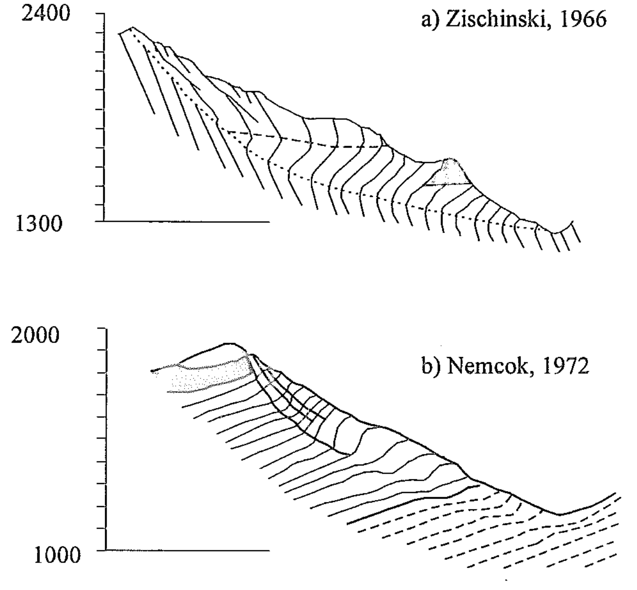


FIG. 2 - Classical examples of flexural pattern reported in literature to explain the characteristics of movement in deep seated gravitational deformations by: a) ZISCHINSKY, 1966; b) NEMCOK, 1972.

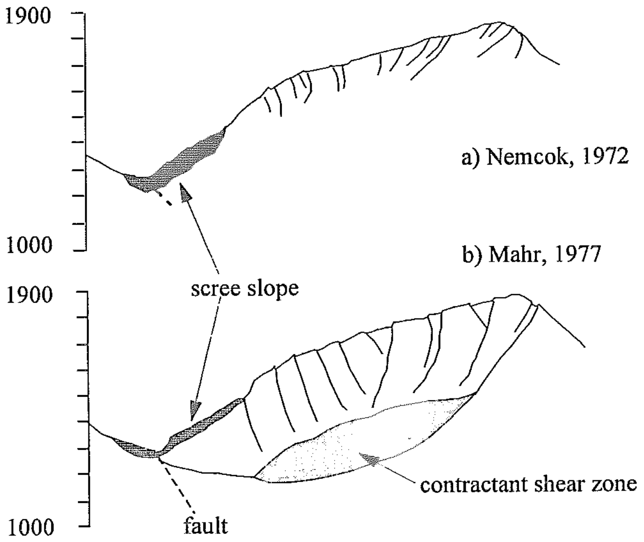


FIG. 3 - Mechanism of evolution of deep seated phenomena proposed in the literature to explain the loss of volume. The evolution of the concept is shown by different interpretations of the same case history: a) Chabenec Ridge by NEMCOK (1972); b) as modified by MAHR (1977).

FEDA (1973) proposed a model (fig. 4) for the development of large slope failures by combining different precedent models. Failure initiates (fig. 4a) by development of a major tension crack near the ridge and advances by volume decrease and the formation of a shear surface at the toe (fig. 4b). Again, no explanation is given for the decrease in volume while shear planes and tension cracks form before the development of the hypothetical contractant creep zone (fig. 4b, c). As a consequence, no bulging toe is described even if most of the deep seated gravitational deformations are described as bulged or having the toe covered by scree slopes and debris (e.g. fig. 3a, 3b). Eventually, in contradiction with what is the basis of progressive shear plane growth, failure evolves downward (fig. 4c, d) instead of upward as a consequence of stress concentration at the surface tip.

RADBRUCH HALL (1978) critically revised that the time existing literature discussing about creep phenomena in rock mass and suggesting that movement takes place over a relatively uniform material, by plastic deformation or

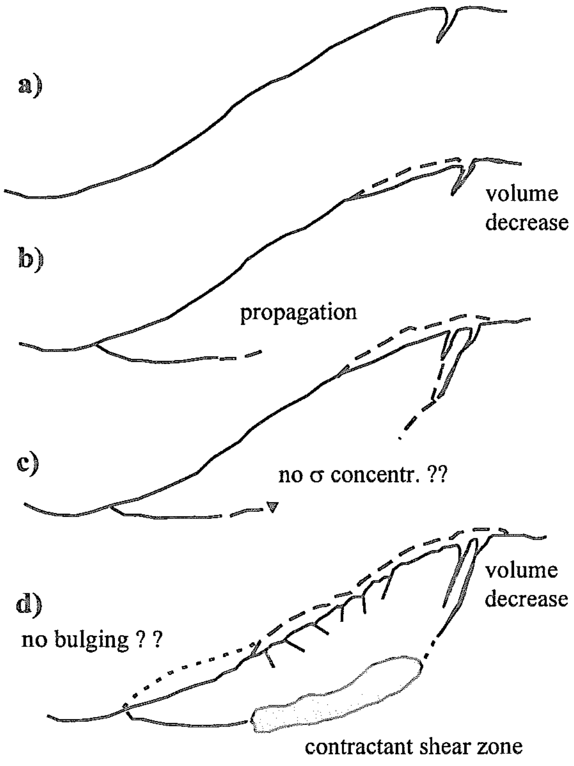


FIG. 4 - Slope failure progress for deep seated deformations according to FEDA (1973). Also reported are some comments about more critical or weaker points existing in the model.

movement along several discrete thin zones or island-like shear planes. Finally, she discussed about toe bulging and proposes the possibility that this can go unnoticed because internal deformation could absorb the movement of the upper slope sectors when this is at its earlier stages.

SAVAGE & VARNES (1987) proposed an analytic solution for gravitational deformations in elastic - plastic materials by conformal mapping and discussed the relation of slope and strength with extension of zones of potential failure in symmetric ridges. SAVAGE & SMITH (1986) completed the work by finding two characteristic line families, for an associated flow rule, correspondent to uphill and downhill facing scarps, these last ones being absent for the case of highly developed steep planes which represent the least work solution.

A composite mechanism in three stages of development (fig. 5) might eventually be proposed with a quite general applicability and high effectiveness in rock masses characterised by sub-horizontal bedding. Sub-horizontal shear planes can grow at the slope toe by a creep sliding process as a consequence of high K (σ_1/σ_3 ratio) values, decreasing away from the topographic surface, and derived by elastic rebound. Subsequent development of tension cracks in the upper slope and beyond the slope crest leads to the final outgrowth of shear fractures up to a complete connection between the two antecedent discontinuity systems. As a variant, the second stage can develop in two different ways: with tension fractures starting from the lower point at the very tip of sub-horizontal creep sliding planes or from the top of the slope.

Eventually, some simple numerical simulations can be found in literature taking in account for deglaciation, unloading of tectonic stresses or release of locked-in stresses. In some cases, an improbable decrease of rock mass properties has been introduced considering degradation of the whole rock mass up to reach conditions presently described only for surficial rock masses.

Nomenclature and definitions

At this point it becomes essential the revision of the proposed definitions for such a kind of slope instabilities and mechanisms. Such a revision shows a relatively abundant number of terms (deep seated gravitational deforma-

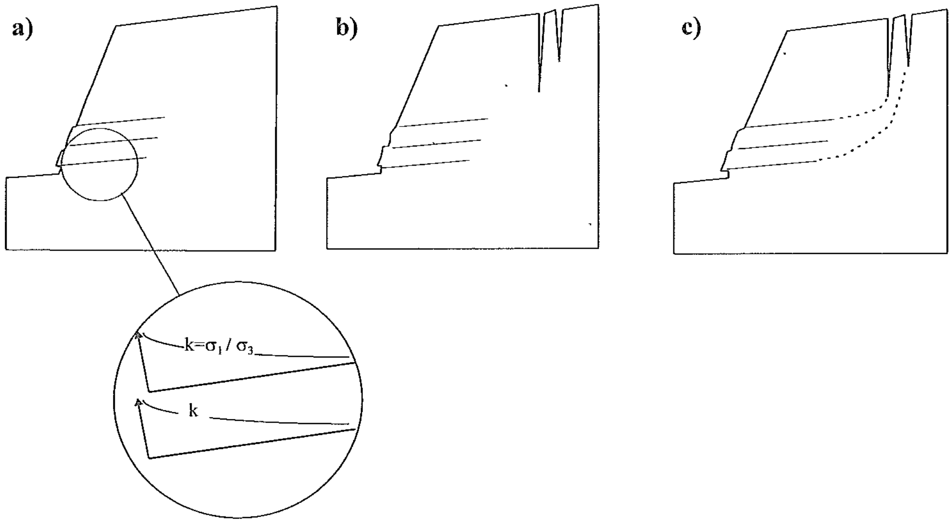


FIG. 5 - Possible three stages mechanism for deep seated slope deformations: a) creep sliding growth of low angle sub-horizontal shear planes as a consequence of the inward decreasing K (s1/s3 ratio; see sketch for K distribution) value originated from elastic rebound, b) tension crack development, c) final outgrowth of shear zones or planes.

tions, deep seated distorsion, mass rock creep, rock flow, etc.) and a quite unclear or limited set of definitions large part of which have been presented in the last decade.

ZISCHINSKY (1966) introduced the term *sackung* with reference to movements with a large amount of continuous deformation along discrete sliding surfaces, distinguishing them from what he calls *gleitung* or sliding along a continuous surface. VARNES (1978) makes reference to such phenomena as rock flow in his landslide classification, recalling a mechanical concept. RADBRUCH HALL (1978) developed an accurate analysis for this kind of phenomena and proposed to mantain a simple terminology as mass rock creep. In fact, Radbruch Hall makes reference to the definitions advanced for rock creep and also advances a range for the measured rates of large scale rock creep (from 2cm/y to 20 cm/d), discussing continuous and incremental creep. Again, she lists a series of settings where mass rock creep has been observed. In 1992, also CHIGIRA preferred to use the term mass rock creep or gravitational mass rock creep to describe creep phenomena and associated structures when rock masses are subjected to a gravitationally unstable state for a long period indifferently from their size and lithology. Once again, a contribution by VARNES & *alii* (1989) introduces the composed definition of deep seated distortion of deep sided ridges, emphasising the primary control played by topography. HUTCHINSON (1988) adopted the term sagging (english word for *sackung*), in his classification of landslides, as a general term for deep seated movements which in their present state of development do not justify classification as landslides, with both a mass creep (deep seated continuous creep, mass creep or progressive creep) and a sliding component of the movement (confined slides). The classification (fig. 6) is based on the position of main upper scarp (before or behind main ridge), shape of the failure surface and resulting mass split up, symmetry and type of up-hill facing scarps. In 1995, HUTCHINSON presents a more complete analysis for deep seated phenomena, dividing them in diastrophic (tectonic) and non diastrophic (gravitational tectonic and gravitational) and advancing two approaches, relative and absolute, for defining deep seatedness.

In Italy, the problem of a better terminological definition started in the 80S (DRAMIS & *alii*, 1985) trying to add more limiting conditions. The last approach (CRESCENTI & *alii*, 1994; DRAMIS & SORRISO VALVO, 1994; SORRISO VALVO, 1995) is to maintain separate definitions for large landslides and deep seated deformation at least for practical reasons. Among the list of these conditions, the indipendence of these deep seated phenomena from morphology is probably the more interesting, being the others recollected from previous descriptions. Nevertheless, it seems an intrinsic property of such phenomena the capability to modify pre-existing morphologies at a large scale or for large slope sectors and then to control actual morphology. One more concern, in the definition of deep seated deformation, has been the so called scale effect. However, scale effects must be differentiated at least in two groups, those concerning description of very large rock mass and slope sectors from those involved in the dynamics of very large rock slides and avalanches (GOGUEL, 1978). The later scale effects, including vaporization or decarbonation, are important in the ultimate, paroxystic, evolutionary phase of very large slides. In fact, presently there is no real data about the possibility that any of the decribed mass rock creep or deep seated gravitational deformation evolved or will evolve to a rock avalanche phase, especially when considering phenomena spreaded to the entire slope. Probably, a more obvious and quoted scale effect is the possible involvement of important tectonic discontinuities (faults, fractures, thrusts, etc.) within the moving mass. These features induce rock mass dishomogeneity, and often represents the weakest structures within a rock mass with increasing probability of intercept with the increase of mass volume and anyway more determinant than single fracture sets. Rigid to ductile transition can not be a distinctive factors because, more than a factor dependent by the scale of the problem, is a function of the mechanical properties of the involved material.

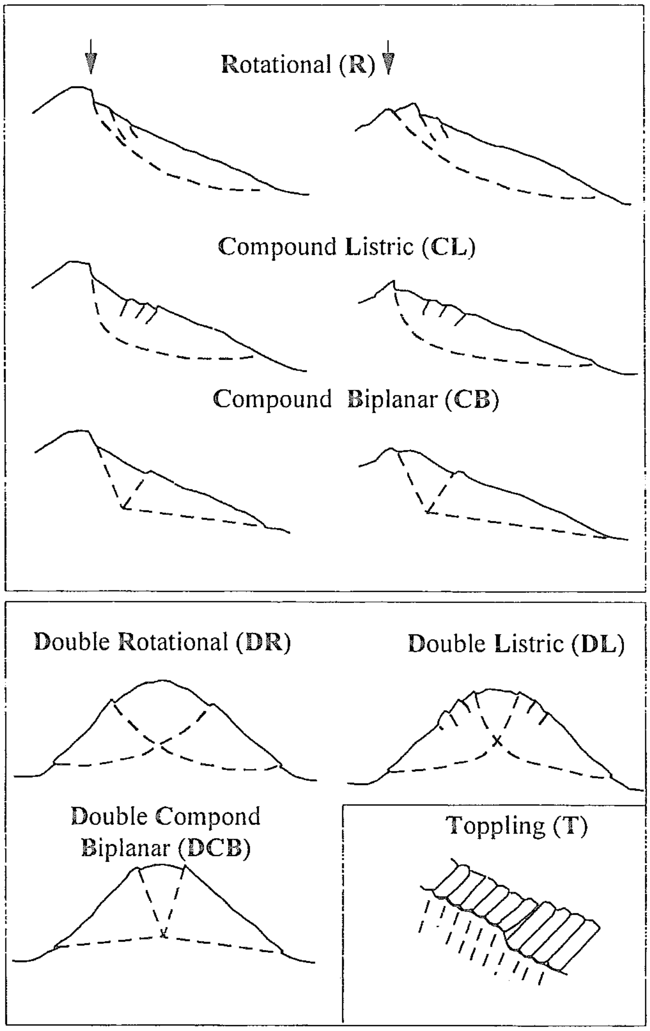


FIG. 6 - Sagging type classification according to HUTCHINSON (1988); arrows point out main scarp location with respect to ridge crest.

Furthermore, the onset of a tertiary creep phase is function of the stress level and velocity of spreading after secondary creep is function of the degrees of freedom, the potential energy, the volume, the topography and the composition of the moving mass. Besides, the importance of kinematic degrees of freedom to evaluate possibility of movement and mass spreading must not be neglected in the analysis.

If we want to find out the limit among different slope instability phenomena, we can start from three points: the reported geometrical descriptions, the existing definitions and some physical-mechanical concept, always remembering the need for differentiating them from common landslides or gravity tectonics processes.

About the geometrical description, the term deep cannot be too precise and a first temptative of discretization has been tried by HUTCHINSON (1995), starting from older works by JANBU & *alii* (1958) and SKEMPTON & HUTCHINSON (1969), and by adopting some geometrical parameters (illustrated in the following).

In regard to the gravitational denotation, gravity acts on the mass generating the weigth force, defined as an internal or body force, which differ from any other external acting factor (seismic, anthropic, etc.). Deformation, from a mechanical point of view, can be seen as distorsion of a continuous body, both homogeneous or dishomogeneous, distributed or localised. At the same time, the concept of discontinuity is important to describe slip or deformation zones, from a mechanical point of view, representing a thin zone or one with discrete width subjected to intense shear and through which we observe a change in a certain parameter (direction and/or magnitude). The concerned parameter that can be of major interest for our purpose is the velocity. In fact, we could have 5 different classes of kinematic discontinuity: continuity, deformation discontinuity, velocity discontinuity, rupture and detachment. In the previously reported models, deformation took place either in a band or within the entire moving mass, according to some plastic or creep law. Once more, creep can occur in different materials at different stress levels and, being gravity the only needed motor, depth can change over various order of magnitude without a real rupture surface is manifested. This is the motivation for which CHIGIRA (1992) chose not to limit phenomena to very deep seated ones but any sort of mass rock creep. Again, what are the differences with a common landslide? Confined sliding surfaces (HUTCHINSON, 1988), creep (discontinuous or incremental), whole mass distorsion, scarps, trenches and counterscarps are, in fact, not exclusive features of deep seated deformations and gravity is always the main agent.

Finally, a short reference can be made about gravity tectonics because of its significance and of the need in separating it from slope deformations. ENGELEN (1969) defines gravity tectonics as a secondary process, involving sidewards movement, occurring at different scale and as a consequence of tectonic vertical uplift. So what can we say about vertical downlift which can still induce sideward movement? Could it just be a further differentiation within gravity tectonics mechanisms?

At the same time we have to remember that tectonic phenomena often include deep crustal sectors as normal fault steps where the toe is firmly established in depth and gravity, which is always acting, acts as a secondary factor in an extensional environment often on blocks of regional interest. This very last observation about block size seems to be the one more commonly mentioned in gravity tectonics decriptions.

STATISTICAL DATA ANALYSIS

Main features and causes

First of all we must emphasise the difficulty in finding usable data from the available technical literature. In fact, few papers result really detailed such to allow a complete evaluation and description of the phenomena, usually lacking most of the information or presenting processes incompatible with at least the very general definition given by HUTCHINSON (1988) for deep seated gravitational deformations (movements which presently do not justify classification as landslides). As a consequence, a large number of the specific papers which describe actual phenomena have not been used as data sources. Furthermore, some distinction have been done among rock flow-mass creep like phenomena and lateral spreading or other more general ones (large slides, creep, etc.). 41 rock flow-mass creep phenomena have been adopted. Large part of these phenomena are located along consequent and obsequent slopes at different dipping angles and mainly with circular and subcircular surfaces (fig. 7a, b). In numerous cases we observed a complete lack of failure surface hypothesis with just a general description of superficial structures.

Rock flow or mass rock creep phenomena prevail in metamorphic rocks (fig. 7c) while lateral spreadings seem to dominate for rigid rock masses over ductile ones. Observed distinctive structures are the more commonly mentioned (fig. 7d) (trenches, scarps, fractures, counterscarps or uphill facing scarps, double ridges, buckling or flexural folds, etc.) with rare reference to precise descriptions of shear zones (CHIGIRA, 1992; CROSTA & BERTO, 1996; cataclastic bands, shear bands, etc.). About controlling factors and causes (fig. 7e) we have observed various (deglaciation, tectonics and neotectonics, relief and geomorphological evolution, etc.) only very general ones with minimum or completely without any support of geomechanical data.

Finally, an attractive observation concerns the interest for instability and deep seated phenomena in volcanic environments (RADBRUCK-HALL, 1978; ELSWORTH & VOIGHT, 1994; BORGIA & *alii*, 1990; MC GUIRE & *alii*, 1996) but these studies are still at their beginning.

Geometry

Statistics of slope movement geometry have been performed on available data for more commonly adopted geometrical descriptors (fig. 8) (Vmax, maximum vertical depth; L, maximum sloping length, from crest to toe; d,

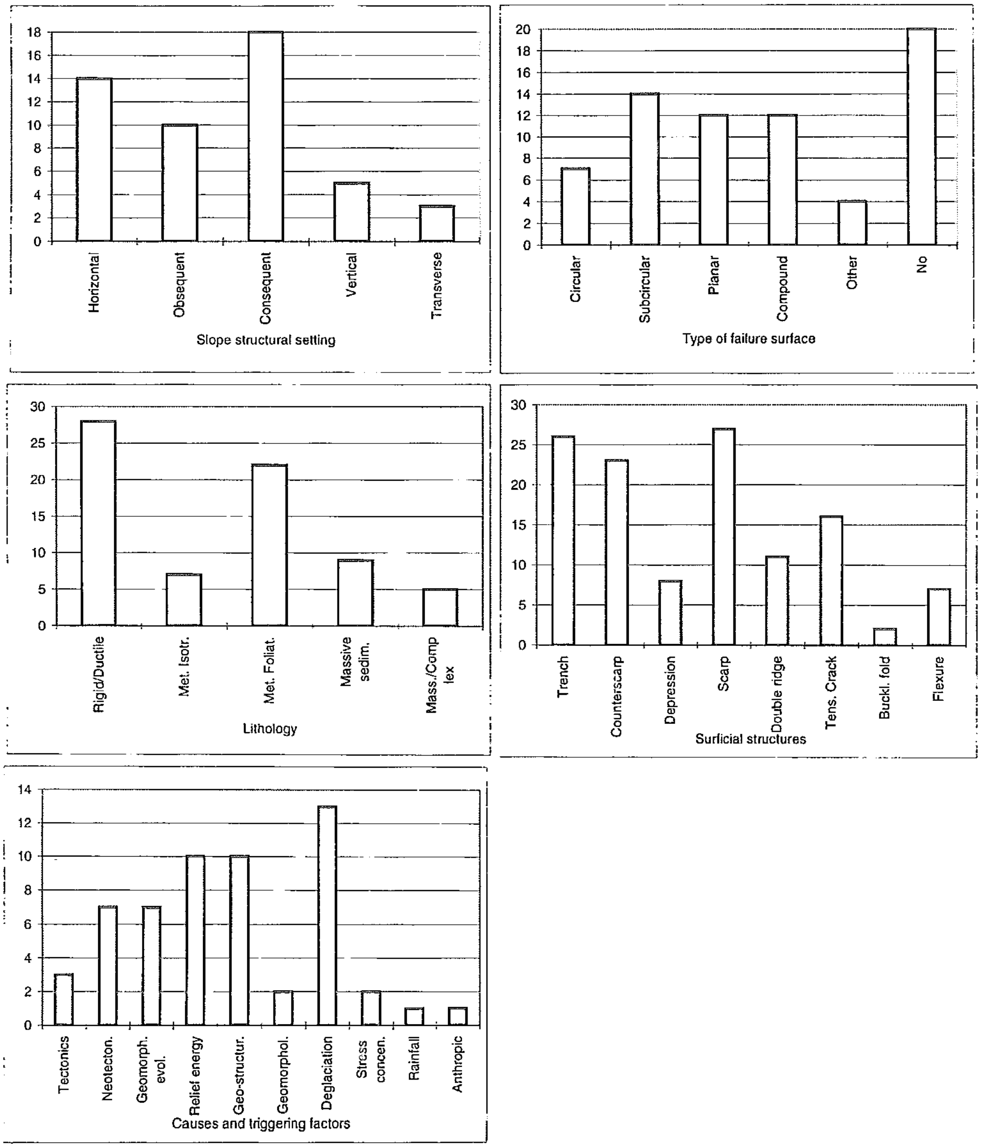


FIG. 7 - Histograms for a) dipping characteristics of the main plane of anisotropy, b) failure surface geometry, c) involved rock mass lithology, d) movement related morphological features and e) controlling factors and causes, as resulting from literature revision.

maximum length between chord L and movement surface, measured normally to L; α, slope of chord L with respect to the horizontal), as reported and reviewed by HUTCHINSON (1995) and commented by CROSTA & BERTO (1996), keeping lateral spreading data separated by rock flow - mass creep ones (table 1 and 2).

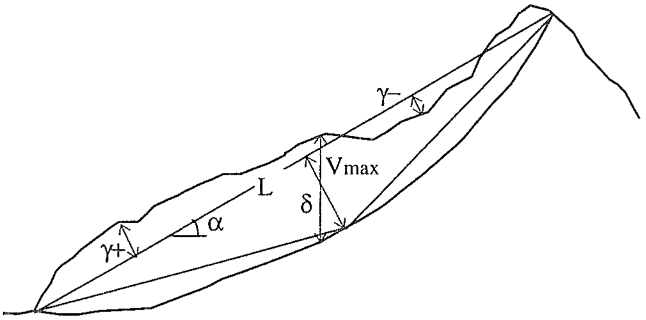
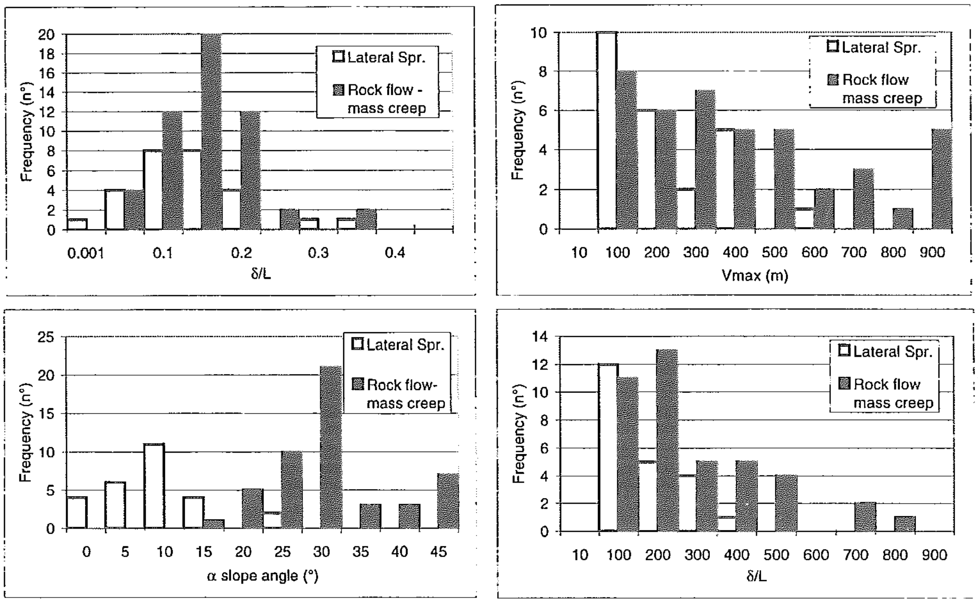


FIG. 8 - Sketch of old and original geometrical parameters proposed for a complete description of the phenomena.

According to their frequency distribution (fig. 9) we can subdivide further both lateral spreading and rock flow - mass creep phenomena. In both classes it has been observed a negative exponential distribution for parameter Vmax and L. In particular, it has been noticed for parameter Vmax an abnormal peak toward the higher values (> 900 m) and probably connected to the major attention placed in the study of very deep seated rock flow - mass creep phenomena. This distribution is similar to the one recorded for parameter δ for lateral spreading, with a better correlation for rock flow - mass creep. Quite different statistical distributions have been recognised for parameter α, between the two classes of processes. A small range of values (0°-17°) has been found logically for lateral spreading

FIG. 9 - Histograms for frequency distribution of main geometric parameters (d/L, a, Vmax, d) as presented in the technical literature about deep seated slope gravitational deformations.



with a flatter gaussian distribution, with respect to that characteristic of rock flow - mass creep processes with average and mode between 25° and 30°. Finally, a normal distribution can be introduced to describe δ/L distribution for both processes, with a wider range for rock flow - mass creep.

A good linear relationship has been found among three variables, Vmax, δ and L, of which Vmax and δ resulted also the more closely linked parameters together with a and δ/L while α represents, logically, the more discretizing parameters between rock flow - mass creep and lateral spreading phenomena (fig. 10a and 10b, 11). Eventually, L resulted poorly discriminating between the two phenomena. The relationship for the whole series of parameters is reported in a correlation matrix plot (fig. 10a) both for rock flow - mass creep and for lateral spreading (fig. 10b). Correlation matrix plot allows to represent all the possible relationships (scatter plots) between each possible couple of parameter, where the parameter distributions are plotted as histograms along the main matrix diagonal. Relationships between specific parameters are reported in figure 11 only for the best correlated ones (Vmax/D and L/D).

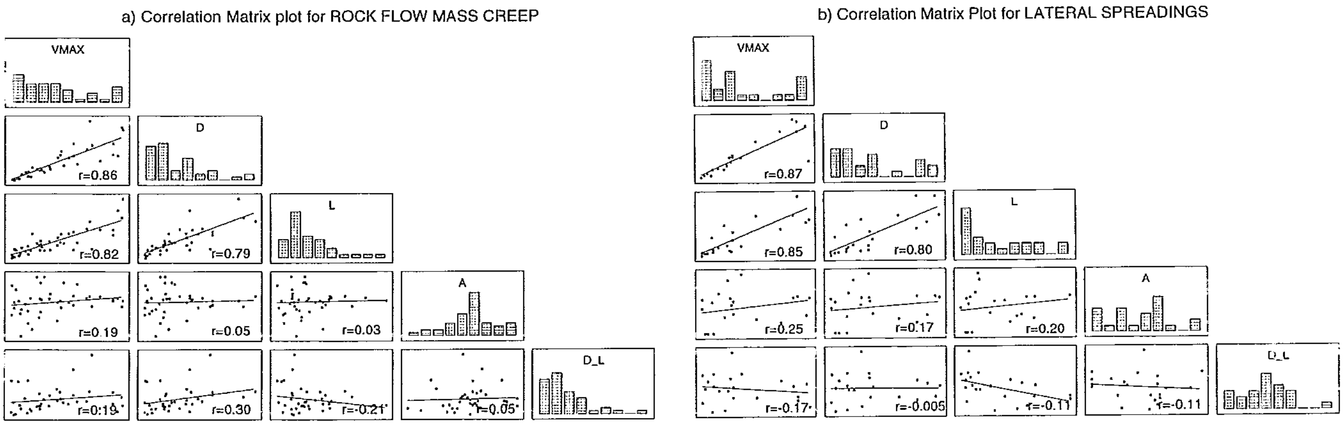


FIG. 10 - Half correlation matrix plots of main geometric parameters in a) rock flow mass creep and b) lateral spreading phenomena. Each plot within the correlation matrix is placed at the intersection of a row with a column and it is obtained by plotting the couple of parameters, located on the main matrix diagonal. Correlation coefficients are presented for each linear regression (D=δ).

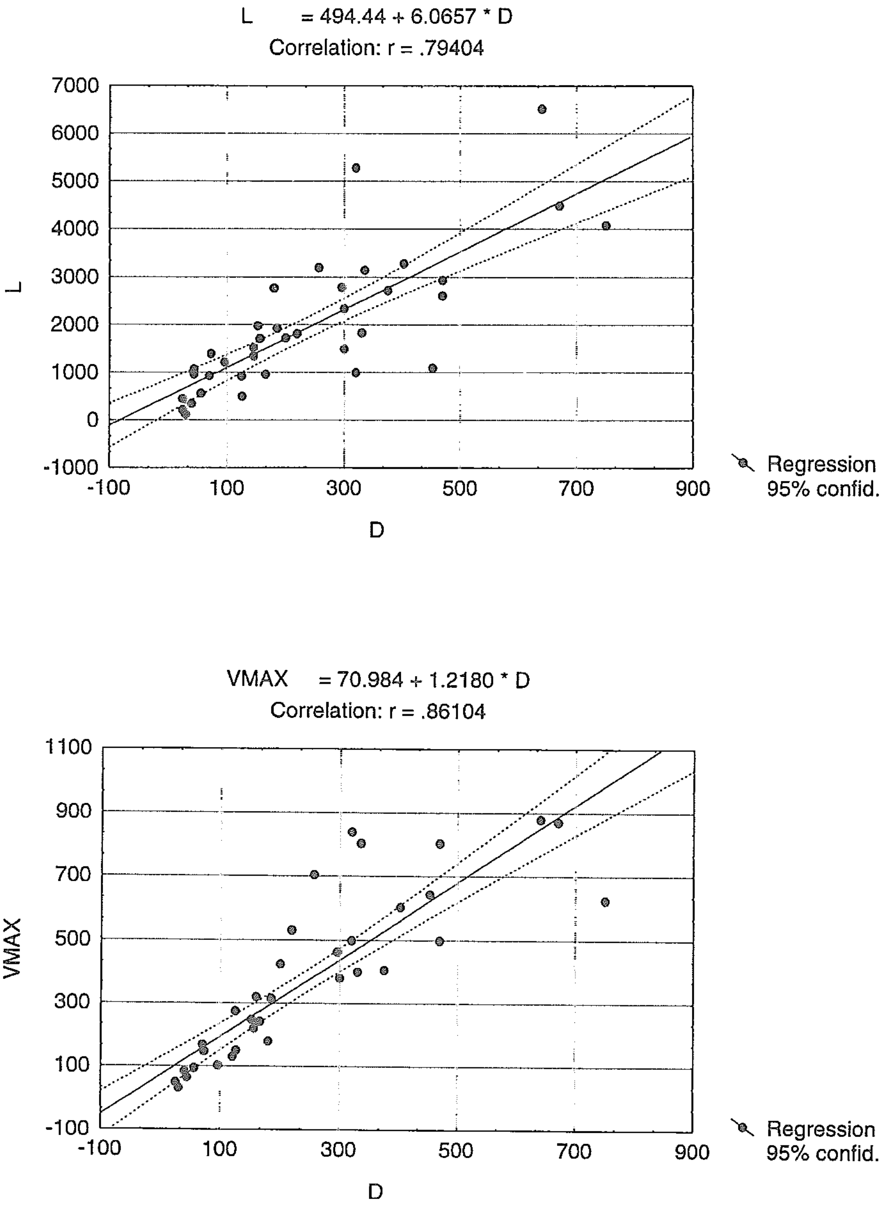


FIG. 11 - Relationships among more related geometric parameters (Vmax/D and L/D) for collected examples of rock flow mass creep penomena.

TABLE 1 - Statistics for rock flow - mass creep geometric parameters

VARIABLE	MEAN	MEDIAN	MODE	ST.DEV.	MIN.	MAX.	1st quartile	2nd quartile
Vmax	353.8	275	multiple	257.4	32.5	880	147	500
δ	232.2	166	multiple	182	25	750	96	320
L	1902.7	1527	1000	1389.8	120	6520	968	2718
α	27.1	28	28	9.1	3	45	23	31
δ/L	0.134	0.116	no	0.08	0.041	0.411	0.08	0.16

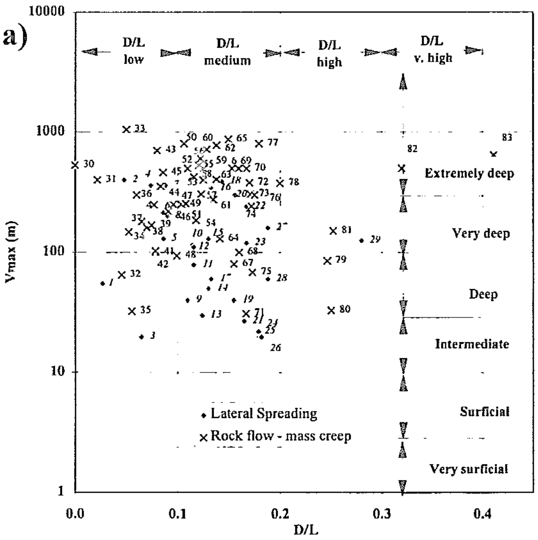
TABLE 2 - Statistics for lateral spreading geometric parameters

VARIABLE	MEAN	MEDIAN	MODE	ST.DEV.	MIN.	MAX.	1st quartile	2nd quartile
Vmax	163.4	122.5	multiple	131.8	20	400	60	300
δ	124.7	99	60	96	18	312	60	200
L	1216.2	841	3400	1017.8	110	3400	350	1944
α	7.2	8.4	0	4.8	0	16.7	4	10
δ/L	0.123	0.127	0.187	0.059	0.0267	0.28	0.086	0.156

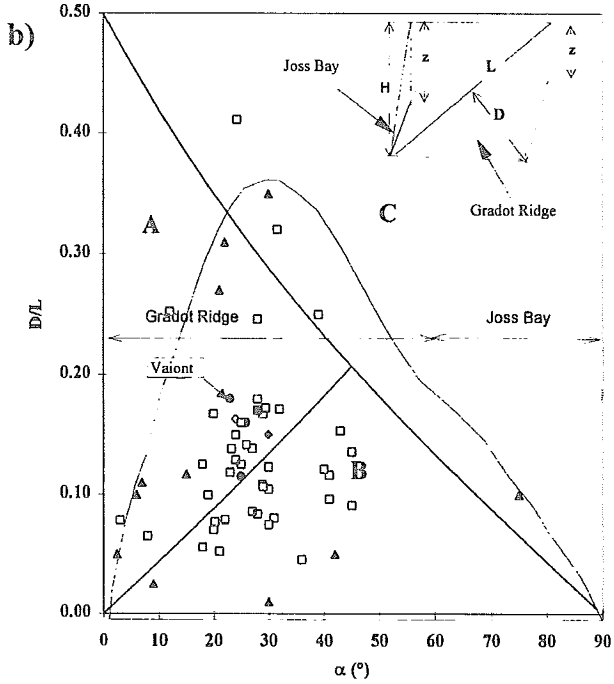
GEOMETRICAL CLASSIFICATION

As above mentioned, the classification of deep seated phenomena has been mainly tried on the basis of geometrical characteristics, concerning both surficial (scarp, counterscarp, trench, graben, etc.) and deep features (failure surface, deformation or shear zone, etc.). The more discerning classifications have been those presented by HUTCHINSON (1988, 1995) and already mentioned above (fig. 6, fig. 12a, fig. 12b). This better discerning action results by the precision in describing the location and type of main surficial features beyond their relationships with the failure surface shape. For such a reason its discussion will be our main aim in the following, simply on the evidence of the performed statistical analysis. In this analysis both lateral spreading and sackung data are used to show a possible boundary between the two phenomena.

For example, starting with the Vmax parameter we observed the presence of multiple modes, both for lateral spreading and rock flow - mass creep, at very different values (table 1 and 2). This note suggests the importance to treat separately different phenomena and putting the limit for extremely deep rock flow - mass creep at a slightly higher value (700 m) instead of the 300 m proposed by HUTCHINSON (1995). In fact, the later value could work just as a first subdivision between phenomena interesting a small or a large sector of a mountain slope. At the same time, it seems important to improve the



1	*Rupe del Corno*	30	Acquaria	57	Moucrons
2	*Bagnone*	31	Maligne Lake	58	Matrei
3	*Turnov*	32	Billan	59	Millstatter
4	*Lastoni di Formin*	33	Green Lake	60	Varadega
5	*Sasso Fra Lupo*	34	Fuipiano	61	La Clapiere
6	*Semelano*	35	Mt.Albenza	62	Matrei
7	*Antelao*	36	Downie Slide	63	V. Susa e Chisone
8	*Kremnicke*	37	Fumaiolo	64	Maratea
9	*Handlova*	38	Fuipiano	65	Padrio-Varadega
10	*Sivy Vrch Mt.*	39	Sechilienne	66	Grand Serin
11	*Luksinek*	40	Golmerhan	67	Nonio 2
12	*Siviy vrch*	41	Klecek	68	Nonio numerico
13	*Lucina*	42	Fuipiano	69	V. Susa e Chisone
14	*Tauk Limmon*	43	Mt. Contact	70	Chabenca
15	*LaVerna*	44	Rosone	71	Samba-gawa
16	*Capo S. Vito*	45	Shinclinon	72	Raztoky
17	*Simoncello*	46	V. Susa e Chisone	73	Coscerno
18	*Rocca Busambra*	47	V. Susa e Chisone	74	Cierny Vah
19	*Drevenik*	48	Washington	75	Nonio1
20	*c.le Spione*	49	Kaunertal	76	Vajont
21	*Bohemian Quarry*	50	Padrio-Varadega	77	Padrio-Varadega
22	*Handlova*	51	Jagerhaus	78	Mt. Cornagiera
23	*Handlova*	52	Branham Ridge	79	Affliction Creek
24	*River Angara*	53	La Clapiere	80	Abukuma Mt.
25	*Motol Valley*	54	Plati'	81	Pomarico
26	*Motol*	55	V. Susa e Chisone	82	Mt. Faloria
27	*Cipollina*	56	Padrio-Varadega	83	Polska Tomanova
28	*Simone*				
29	*Scopello*				



Localita'	α (°)	δ/L	Localita'	α (°)	δ/L
River Beas	30	0.350	Matrei	25	0.125
Joss Bay	75	0.100	Matrei	27	0.138
Le Bouffay	22	0.310	Millstatter	18	0.125
Gradot Ridge	21	0.270	Kaunertal	30	0.104
Vajont	23	0.180	Raztoky	28	0.170
Vajont	26	0.160	Chabenca	20	0.167
Vajont	25	0.115	Affliction Creek	28	0.246
Folkenstone Warren	15	0.117	Samba-gawa	29	0.167
St. Catherine Point	7	0.110	Shinclinon	27	0.086
Bekkelaget	6	0.100	Abukuma Mt.	39	0.250
Furre	2.5	0.050	Rosone	28	0.083
Jackfield	9	0.025	Varadega	24	0.129
Jonas Creek	42	0.050	Fuipiano	20	0.070
Mt. Kitchener	30	0.010	Coscemo	32	0.171
Nonio 1	28	0.170	Grand Serin	43	0.153
Nonio 2	30	0.150	Moucrons	30	0.123
Nonio numerico	24	0.160	Plati'	23	0.118

FIG. 12 - Classification of major deep seated gravitational phenomena reported in the literature according to some geometrical parameters and through different plots as proposed by HUTCHINSON (1995): a) Vmax/(d/L) with reference to the presented list of events (in italic are lateral spreadings, in plain text are rock flow mass creep), b) (d/L)/a. Zone A is the field for circular slides of deep form with upper limit given by (1-sina)/2cosa and divided by zone B, for circular slides of shallow form, through curve (1-cosa)/2sina. Zone C descibe the values for which circular and non circular slides are unlikely. The bell shaped field contains deep seated form of non circular slides.

classification by a combined application of Vmax and δ/L ratio.

It can be stressed that very few phenomena are reported with values of the δ/L ratio greater than 0.2. Furthermore, a more precise description of the failure or shear zone would be reached by calculation of the ratios between δ and the length of the two segments individuated by the intersection of δ with L, giving a better idea about circularity and general geometry of the failure surface. The definition of δ is clearly linked, indeed, to the chosen failure surface or zone, being not necessary a sliding plane, drawn on the basis of some subjective and objective assumptions.

It could be suggested that two more measurements for maximum toe bulging (γ+), in the lower hillslope, and maximum convexity (γ–) in the upper hillslope (fig. 8) would be taken when describing a particular deep seated phenomenon. In fact, these parameters could point out something more about mass balance within the moving mass or the main evolutionary mode (toe bulging, sliding or fall at the slope toe, appearance of scarp along the upper slope, dilation of the rock mass, etc.).

Eventually, it must be stressed that more commonly proposed failure surfaces have a circular to subcircular shape (fig. 7b). This seems peculiar because it excludes the possible and probable presence of major controlling features like foliation, bedding, faults or thrust planes as often observable in the field.

DEEP SEATED INSTABILITY ON VOLCANOES

Different kinds or association of mechanisms must be invoked in some particular environments. Volcanoes, and volcanic edifices (domes, crypto-domes, etc.) represent a special environment where thermo-hydro-mechanical coupling detains a major control on the behaviour of rock masses. Hence, this coupling controls the evolution of both slow and very rapid instability phenomena as well as of shallow and deep instabilities. Nevertheless, very little attention has been focussed on such a subject (McGuire & *alii*, 1996) and this is a relatively virgin terrain where few has been done and where many external forces become involved both as co-acting causes and as controlling factors of the mechanical behaviour. Then more complex and specific laboratory tests are needed when confronting such type of problems.

A list of causes that can contribute directly to volcanoes instabilities is beyond the aim of this paper but we can enumerate some: the natural quaquaversal dipping of the deposits sedimented at their angle of repose or just above this limit because of their high temperatures, the intercalation of layers (lava flows, cineritic and pyroclastic deposits both welded and loose) with quite different geomechanical, thermo-mechanical and hydraulic properties, dyke or magma intrusion with consequent dilation and lateral pushing action, hydrothermal alteration and consequent weakening of deposits and of the volcanic edifice, increase in water and vapour pressure as well of temperature during different activity phases of the volcano, repeated seismic shaking, dragging action during pyroclastic column collapse, subsidence, movement along some major tectonic features (faults, rifts, etc.) connected to volcano formation, increase in weight of some particular cone sector for deposition of different sediments and as a consequence of changes in volcanic activity. Ultimately, the continuous accumulation of volcanic sediments and the resultant lateral growth of the edifices could implicate their deposition on soft sediments with low geomechanical properties and the consequent volcano slope instability together with deformation of underlaying sediments.

The analysis and the understanding of such phenomena could be improved by a detailed monitoring able to support valuable numerical analyses.

NUMERICAL MODELLING

First aim of the above discussed research has been to find out the main geometric and geologic features as well as the more common characteristic parameters both for the rock mass and discontinuity properties. These features compose in fact the essential data set for input in numerical as well as physical modelling.

The result has been the identification of only some of these parameters: transversal isotropy of rock masses with importance of consequent and obsequent slopes (especially obsequent), prevailing metamorphic rocks, average slopes (ranging between 3°-45° with modal 28°), presence of flexural structures (flexure, drag, inflexion folds), high degree of rock fracturing close to the surface, importance of residual and locked in stresses and of stress release. As above mentioned, no real values have been found in literature for geomechanical parameters (material strength, degree of fracturing, etc.) concerning the «failure» surface or zone and the rock mass, and very few ones for velocity, displacement and influence or extension of geologic structures (Bovis, 1982, 1989). This fact is also due to the intrinsic difficulties and the economic costs involved in deep investigations.

These information has been used in the generation of very simple numerical models such to conduct some parametric studies mainly concerning the effect of the orientation of the plane of transverse isotropy, the effect of glacial unloading, the change of rock mass properties and their decrease close to the topographic surface and the size and symmetry of the ridge.

The rock mass properties introduced in the numerical simulations, performed by mean of a diffused commercial geomechanical software (Flac, Itasca, 1993), has been evaluated through the Hoek & Brown empirical criterion starting from more diffused and typical lithologies and some medium values of the Rock Mass Rating (RMR) according to the Bieniawski classification (1979). This approach has been chosen for the importance of considering different rock mass properties during parametric modelling. It must be stressed that such empirical criterion is useful just to se-

TABLE 3 - Rock mass geomechanical properties adopted for numerical modelling

MODEL	RMR	σ_c (MPa)	m_i	ϕ (°)	c (MPa)	t (MPa)	K (Mpa)	G (MPa)	θ (°)	ϕ_j (°)	t_j (MPa)
1	60	150	8	40	4.8	0.5	12000	7000	0-90	40	0.5
2	40	150	8	38	2.6	0.3	4000	2200	0-90	40	0.5
3	30	150	8	33	0.6	0.1	3500	2000	0-90	30	0.5

lect the range for rock mass strength parameters, being the user discouraged to adopt it for strongly anisotropic rock mass conditions. As a consequence, a more general Mohr Coulomb failure criterion has been adopted for modelling rock mass behaviour in the calculations on the basis of parameter values computed by the Hoek & Brown approach.

The geomechanical parameters adopted for the modelling are listed in Table 3 (σ_c: uniaxial compressive strength for intact rock; m_i: Hoek & Brown constant for lithology and joint properties; ϕ: angle of internal friction for intact rock; c: rock mass cohesion; t = rock mass tensile strength; K: rock mass bulk modulus; G: rock mass shear modulus; θ: ubiquitous joint dip angle; ϕj: joint friction angle; tj: joint tensile strength), while planes of transverse isotropy have been rotated through 90° (θ), for symmetrical ridges, resulting in both obsequent and consequent slopes.

The most evident consequence of transverse isotropy was the asymmetric behaviour. This behaviour is sometimes masked by the good rock mass properties or the faible ubiquitous joints dipping. Maximum anisotropic behaviour was evidenced for average joint dipping angles (40°) close to slope inclination (40°). Such a condition evidenced some very interesting situations with bulging and sliding along consequent slopes and large block sliding on discrete shear zones along obsequent slopes (fig. 13a, b, e, f). Rock mass properties and the adopted failure criterion controlled the extension of the deformation as well as its localization (fig. 13d, h), even if more particular care must be placed in the numerical modelling. Bulging was the first consequence of deglaciation, with arching larger at the base of the consequent slope, followed by sliding along the entire slope (fig. 13a, b, c, d, e, f, g, h) with a maximum displacement in the upper sectors and inducing more buckling at the slope toe. Progressive failure was regularly observed especially on obsequent slopes, starting from the toe, with stress concentration moving progressively uphill. In some particular cases where upper slope instability induced loading conditions on the lower slope sector, it has been observed the progressive downhill propagation of the failure zone. Zones characterized by tensile stresses and consequent tensile failure were identified in correspondence both of the top ridge and the toe bulging, while the formation of an S-shaped pattern for ubiquitous joints (fig. 13b, f) was generated by buckling, dragging, bending in the entire slope. This very last observation agrees with what has been suggested and described in the literature by many different authors (ZISCHINSKY, 1966, 1969; NEMCOK, 1972; MAHR, 1977; CHIGIRA, 1992; CROSTA & BERTO, 1996). Flexure of the anisotropy planes was generally accompanied and sometimes induced by sliding of the more surficial or higher slope sectors, with consequent strain localization in a relatively thin shear zone. For example the case presented by Zischinsky (fig. 2b), as some other in literature (PUMA & *alii*, 1989) seems to be explainable also through sliding of the upper slope sector and dragging-flexuring of the underlaying rock mass material. In other simulations with rock masses of different properties minimum displacements were observed but with larger and deeper slope sector affected by movement.

DISCUSSION AND CONCLUSIONS

Aim of this work was to reach a better comprehension of these phenomena, for the formulation of some hypothesis and revealing some blank spots requiring more investigation. Major definitions, proposed mechanisms, examples and concerning data have been collected, revised and introduced to begin and support some initial numerical analyses performed with a parametric approach.

Even if a lot has been written about rock flow-mass creep-sagging or deep seated deformation still a lot has to be done, with obviously no fault charged to the previous researchers. Up to now it seems more correct to classify a phenomenon as deep seated on a subjective basis simply for no similarity with common landslides, and mainly on some qualitative observations lacking any precise limit for a clear separation between deep seated gravitational phenomena and large landslides. Data concerning displacement, velocity, depth, presence of tectonic structures, physical and mechanical properties of the rock mass are almost completely absent, leaving so much space for future research and hope for a more quantitatively based definition of deep seated deformations and classification of the phenomena.

As a consequence, very few models have been suggested for the onset and evolution of deep seated instabilities making still more difficult their classification.

Researchers need to pay more attention to causes, even if already cited or described. For example, the presence and especially the mechanical influence of faults must be regarded as very important. In fact, faults are weak structures that can work as starting points for the deformation to take place without need for their integral reactivation but just forming a segment of the entire failure surface. Complete fault reactivation seems more a problem connected to neotectonics or gravity tectonics.

However deep seated are these processes, the creep that is taking place is more probably of the brittle type and

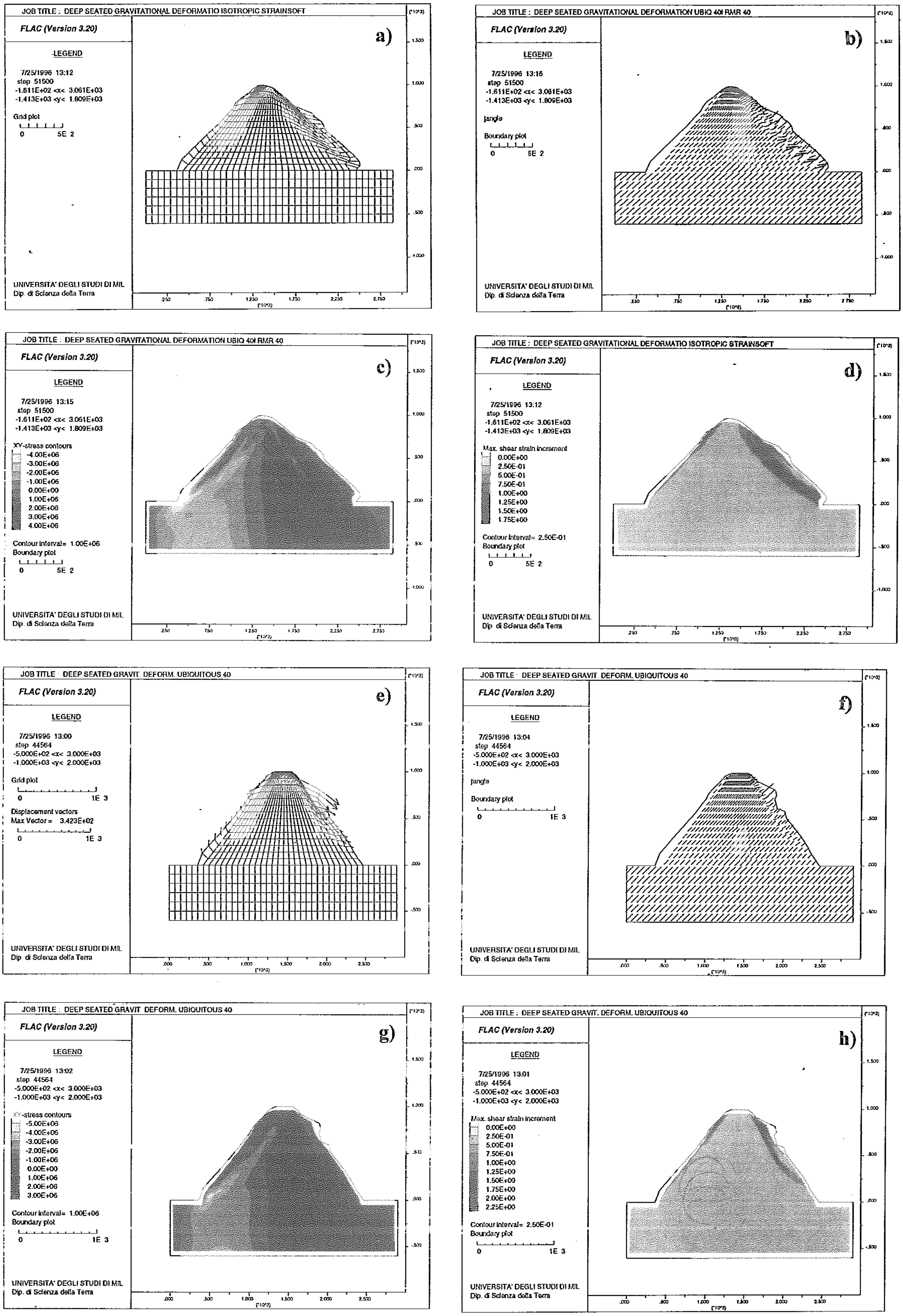


FIG. 13 - Particular of the results from some finite difference numerical modelling for a symmetric ridge 1000 m high and planes of transversal isotropy inclined at 40° (consequent slope to the left, obsequent to the right) with two different geomechanical rock mass classes a-d) RMR = 60 e-h) RMR = 40; (see table III for input geomechanical parameters). Sketch a) and e) deformed grid; b) and f) isotropy planes deformation pattern; c) and g) shear stress distribution; d) and h) max shear strain increment.

it can be accelerated by changes in water or gas pressure and seismic activity. This show the importance of monitoring, besides for the study of future evolution of the phenomena, for a better understanding of the importance of such external factors on slow deep seated deformations and then on the effectiveness of their interaction with the processes. Indirectly, this effectiveness could be a first way to discern between deep seated and more surficial processes according to the degree of subsequent disturbance. In fact, more surficial phenomena are more sensitive to external disturbances as rainfalls or anthropic actions, while the opposite is true for very deep ones.

Furthermore, deglaciation is often proclaimed as one major cause but almost nothing has been said about the resulting changes in the piezometric surface and in the rock mass permeability as a consequence of fracture opening. It is retained indeed that these changes could play a major role in instabilization and evolution of rock slopes.

Mechanisms, as above described and discussed, form the next step in the understanding of the process, but still so much confusion and indeterminacy do exist on the matter. Creep development, in situ stress state, mechanical properties and behaviour of the rock mass have not been considered in detail in past studies, according a great preference to geomorphological and descriptive works.

For example, we must remember that creep in rock occurs with three different deformational components: elastic, plastic and anelastic dilatancy related to the growth of interacting systems of micro-fractures up to the development of a complete rupture surface. Meanwhile, creep in rock masses is the result of summing intact rock creep phenomena to the sliding and viscous deformation of the discontinuities as influenced by volumetric fracture intensity, anisotropy, mechanical properties and the occurrence of cataclasis along major discontinuity planes. Numerical modelling can be a useful means to a better understanding of such a type of phenomena and so much has still to be done about deep seated instabilities with its support. The numerical modelling allowed for the computation and the visualization of many different parameters as displacement, velocity, failure conditions (tension, compression, sliding, yield), stress distribution and concentration, shear strain increment and rate, etc. Besides, simulations can allow a better understanding of the process showing its development through time and this can be fundamental when introducing creep behaviour. This research just showed some of the main results and of the future possible steps to undertake.

Phenomena in our concern show a very slow evolution which is rarely perceptible to us but for the presence of some particular morphology. Furthermore, there is no clear sign that such phenomena can turn out in very dangerous failures as rock avalanches, and why not, this could be considered as one more way to differentiate between large rockslides or rockfalls or complex slides and deep seated deformations. In fact, this implies some difference in the degrees of freedom for each typology and then the admissible future kinematism. For example, it sounds strange that a shear zone (coincident with the major plane of movement) will be able to generate a rock avalanche if it daylights at the talweg and no other rupture surface is forming uphill. Risk is coupled to this kinematic feasibility and to the mechanics of the process and for this reason monitoring, mechanical models and interpretation of displacement data are of major interest to discriminate between rapidly accelerating or steady moving phenomena.

Eventually, also in accordance with what above said, scale effects seem to be reconsidered in a quite different way to the one sometimes suggested in the literature. In fact, it must be emphasised the importance of increasing probabilities in embracing weak tectonic structures or intensely fractured rock masses with increasing size of involved slope sectors. Again, an increase in size is fundamental for an increase in the stress level and then the possibility to start creep processes can spread to rock masses that otherwise will behave in a rigid elastic way.

At this point, it comes back the importance of a correct definition of the process which stresses the role of the term deformation, with respect to the more commonly used sliding or failure, together with the adjectives deep seated and gravitational. At the very end, it must be remarked that up to now a very general and sometimes improper use of such a definition has been done and this because of a definitive lack of data and verification, both in situ and through test or numerical simulations, and for the incompleteness of surficial observations and among them of any monitoring.

REFERENCES

Amadei B., Savage W.Z. & Swolfs H. (1987) - *Gravitational stresses in anisotropic rock masses*. Int. J. Rock Mech. Min. Sc., 24, 1, 5-14.

Amadei B., Swolfs H. & Savage W.Z. (1988) - *Gravity induced stresses in stratified rock masses*. Rock Mech., 21, 1-20.

Amadei B. & Pan E. (1992) - *Gravitational stresses in anisotropic rock masses with inclined strata*. Int. J. Rock Mech. Min. Sci., 29, 3, 225-236.

Aydan (1992) - *The stability of slopes and underground openings against toppling and their stabilization*. Rock Mech., 25, 3, 143-165.

Beck A.C. (1968) - *Gravity faulting as a mechanism of topographic adjustment*. New Zeland Jour. Geol. Geoph., 11(1), 191-199.

Bemmelen R.W. Van (1950) - *Gravitational tectogenesis in Indonesia*. Geol. Mijnb., 12, 351-361.

Borgia A., Burr J., Montero W., Alvarado G.E. & Morales L.D. (1990) - *Fault propagation folds induced by gravitational failure and slumping of the Central Costa Rica volcanic range: implication for large terrestrial and martian volcanic edifices* Journ. Geophys. Res., 14357-14382.

Bovis M.J. (1982) - *Uphill-facing (antislope) scarps in the Coast Mountains, southwest British Coulumbia*. Geol. Soc. Am. Bull., 93, 804-812.

Bovis M.J. (1989) - *Rock-slope deformation at Affliction Creek, southern Coast Mountains, British Coulumbia*. Geol. Soc. Am. Bull., 93, 804-812.

Cancelli A. (1980) - *The monitoring of the Spriana landslide*. Proc. Int. Symp. on Landslides, New Delhi, 7-11 April 1980, 3, 216-219.

Cancelli A. & Pellegrini M. (1987) - *Deep-seated gravitational deformations in the Northern Apennines, Italy*. Proc. 5th Icfl, Australia & New Zeland, August 1987, 1-8.

Cancelli A. & Casagli N. (1995) - *Classificazione e modellazione di fenomeni di instabilità in ammassi rocciosi sovrapposti ad argilliti o argille sovraconsolidate*. Mem. Soc. Geol. It., 50, 67-82.

CANUTI P., GARZONIO C.A. & VANNOCCI P. (1989) - *Deep-seated gravitational phenomena and ancient landslides of Chiusi della 'Verna mountain (Tuscany, Italy).* Proc. 2nd Icg, Frankfurth, September 1989.

CARDINALI M., DRAGONI W. & GUZZETTI F. (1989) - *Prime osservazioni sui probabili fenomeni gravitativi di versante del Monte Coscerno (Valle del Nera, Appennino umbro-marchigiano).* Boll. Soc. Geol. It., 108, 373-378.

CASAGLI N. (1993) - *Meccanismi di instabilità indotti dal contrasto di competenza in ammassi rocciosi su un substrato deformabile.* PhD thesis Eng. Geology, 1990-1993.

CHIGHIRA M. (1992) - *Long-term gravitational deformation of rock by mass rock creep.* Eng. Geol., 32 (3), 157-184.

CRESCENTI U., DRAMIS F., PRESTININZI A. & SORRISO VALVO M. (1994) - *Deep seated gravitational deformations and large scale landslides in Italy.* Int. Congr. Iaeg, Special Volume, Lisboa, 71 pp.

CROSTA G. & BERTO R. (1996) - *Lineamenti tettonici e materiali di faglia: fattori di controllo nelle deformazioni gravitative profonde. L'esempio della frana di Nonio (Novara, Italia).* Quad. Geol. Appl., Pitagora, 3 (1), 49-83.

DRAMIS F., MAIFREDI P. & SORRISO-VALVO M. (1985) - *Deformazioni gravitative profonde di versante. Aspetti geomorfologici e loro diffusione in Italia.* Geol. Appl. Idrogeol., 20, 377-390.

DRAMIS F. & SORRISO-VALVO M. (1994) - *Deep seated slope deformations, related landslides and tectonics.* Eng. Geol., 38, 231-243.

ENGELEN (VON) G.B. (1963) - *Gravity tectonics in the North-Western Dolomites (N.Italy).* Geol. Ultraiec., 13, 1-92.

ELSWORTH D. & VOIGHT B. (1994) - *Dike intrusion as a trigger for large earthquakes and the failure of volcano flanks.* Journ. Geophys. Res., 100, B4, 6005-6024, April 10, 1995.

EMERY J.Z. (1978) - *Simulation of slope creep.* In: Voight B. (ed.) «Rockslides and Avalanches Natural Phenomena». Devel. in Geotech. Eng., 14, Elsevier, Amsterdam.

FERGUSON H.F. (1967) - *Valley stress release in the Allegheny Plateau.* Eng. Geol., 4, 63-71.

FEDA J. (1973) - *Stability of natural slopes.* Proc. 8th Int. Conf. Smfe, Session 6, Oral discussion, Moskva.

FORCELLA F. (1984) - *The Sackung between Mount Padrio and Mount Varadega, Central Alps, Italy: a remarkable example of slope gravitational tectonics.* Méditerranée, 51 (1-2), 81-92.

FORCELLA F. & ROSSI P.M. (1987) - *Le deformazioni di versante presenti nel territorio di Fuipiano Imagna (Prealpi Bergamasche).* Boll. Soc. Geol. It., 106, 281-291.

FUKUZONO (1985) - *A new method for predicting the failure time of a slope.* Proc. 4th Icfl, Int. Conf. & Field Workshop on Landslides, Tokyo, 145-150.

FURLINGER W.L. (1972) - *Mechanismus einer Hangbewegung in Quarzphylliten un dessen Kontrolle im Gefugeaquivalenten Modellversuch.* Geol. Rundsch., 69, 871-882.

GOGUEL J. (1978) - *Scale-dependent rockslide mechanism with emphasis on the role of pore fluid vaporisation.* In: Voight B. (ed.) «Rockslides and Avalanches Natural Phenomena». Devel. in Geotech. Eng., 14, Elsevier, Amsterdam.

GUERRICCHIO A., MELIDORO G. & RIZZO V. (1986) - *Slope instability and earthquakes in the Valley of Maratea (Basilicata region,Italy).* Proc. of the Int. Symp. on «Engineering Geology Problems in Seismic Area», Bari, Geol. Appl. Idrogeol., 21 (2), 57-62.

GUERRICCHIO A., MELIDORO G. & RIZZO V. (1987) - *Sulla dinamica geomorfologica recente ed attuale della Valle di Maratea (Lucania).* Boll. Soc. Geol. It., 106, 293-302.

HAEFELI R. (1965) - *Creep and Progressive failure snow, soil, rock and ice.* Proc., 6th Icsmfe, (3), Montreal, 134-148.

HOFMAN H. (1973) - *Modellversuche zur Hangtektonik.* Geol. Rund., 62, 16-27.

HUTCHINSON J.N. (1988) - *General Report: morphological and geotechnical parameters of landslides in relation to geology and hydrogeology.* Proc. 5th Int. Symp. on Landslides, Lausanne, Balkema, 1, 3-35.

HUTCHINSON J.N. (1995) - *Deep-seated mass movements on slopes.* Mem. Soc. Geol. It., 50, 149-166.

ITASCA (1993) - *FLAC: Fast Lagrangian Analysis of Continua, v. 3.2. User manual.* Itasca Consulting Group. Inc., Minneapolis (USA).

JAHN A. (1964) - *Slopes morphological features resulting from gravitation.* Zeit. Geomorph. Suppl., 5, 59-72.

JANBU N., BJERRUM L. & KJAERNSLI B. (1958) - *Veiledning ved losning av fundamenteringsopvager.* Norwegian Geotech. Inst., publ. 16, 1-93.

KNILL J.L. (1968) - *Geotechnical significance of some glacially induced rock discontinuities.* Bull. Ass. Eng. Geol., 5, 49-62.

KOSTAK B. (1977) - *Photoplastic slope deformations models.* Iaeg Bull., 16, 221-223.

MAHR T. (1977) - *Deep-reaching gravitational deformations of high mountain slopes.* Iaeg Bull. 16, 121-127.

MAHR T. & NEMCOK A.(1977) - *Deep-seated creep deformations in the crystalline cores of the Tatry Mts.* Iaeg Bull., 16, 104-106.

McGUIRE W.J., JONES A.P. & NEUBERG J. (1996) - *Volcano instability on the Earth and other Planets.* Geol. Soc. Spec. Publ. 110, 388 pp.

McTIGUE D.F. & MEI C.C. (1981) - *Gravity-induced stresses near topography of small slope.* Journ. Geoph. Res., 86, NO. B10, 9268-9278.

MENCL V. (1968) - *Platizitatslehre und das wirkliche Verthalten von Geibirgsmassen.* Felsmech. U. Ing. Geol. Suppl. IV, 1-8.

MORTARA G. & SORZANA P.F. (1984) - *Slope instability in high mountain environments: deep seated gravitational deformation in western Alps Italy.* Cnr-Pan Meeting on Progress in Mass Movements and sediment transport study, Torino, 77-94.

NEMCOK A. (1966) - *The development of landslides on the boundaries of geological formations.* Sbornik Geologickych Ved., Rada HIG, 5, Prague.

NEMCOK A. (1972) - *Gravitational slope deformation in high mountains.* Proc. 24th Int. Geol. Cong., Montreal, Sect. 13, 132-141.

NEMCOK A & PASEK J. (1969) - *Deformacie horskych svahov.* (In Slovak). Geol. Prace, Spr. 50, Bratislava, 5-28.

NEMCOK A. & RYBAR J. (1968) - *Landslide investigation in Czechoslovakia.* Proc. lst Session Iaeg, Prague, 183-198.

PAN E., AMADEI B. & SAVAGE W.Z. (1994) - *Gravitational stresses in long symmetric ridges and valleys in anisotropic rock.* Int. Journ. Rock Mech. Min. Sc., 31 (4), 293-312.

PAN E., AMADEI B. & SAVAGE W.Z. (1995) - *Gravitational and tectonic stresses in anisotropic rock with irregular topography.* Int. Journ. Rock Mech. Min. Sc., 32 (3), 201-214.

PASEK J. (1968) - *Schollenartige Hangbewegungen.* Mitt. Ges. Geol. Bergbaudstud., 18, 367-378.

PASUTO A. & SOLDATI M. (1990) - *Rassegna bibliografica sulle Deformazioni Gravitative Profonde di versante.* Il Quaternario, 3(2), 131-140.

PRITCHARD M.A. & SAVIGNY K.W. (1991) - *The Heather Hill landslide: an example of a large scale toppling failure in a natural slope.* Can. Geotech. Journ., 28, 410-422.

PUMA F., RAMASCO M., STOPPA T. & SUSELLA G. (1989) - *Movimenti di massa nelle alte valli di Susa e Chisone.* Boll. Soc.. Geol. It., 108, 391-399.

RADBRUCH-HALL D. (1978) - *Gravitational creep of rock masses on slopes.* In: Voight B. (ed.) «Rockslides and Avalanches Natural Phenomena» Devel. in Geotech. Eng., 14, Elsevier, Amsterdam, ch. 17, 607-657.

RADBRUCH-HALL D., VARNES D.J. & SAVAGE W.Z. (1976) - *Gravitational spreading of steep-sided ridges («Sackung») in Western United States.* Iaeg Bull., 14, 23-35.

RADBRUCH-HALL D., VARNES D.J. & COLTON R.B. (1977) - *Gravitational spreading of steep-sided ridges («Sackung») in Colorado.* Jour. Res. U.S. Geol. Survey, 5, 359-363.

RAMASCO M., STOPPA T. & SUSELLA G. (1989) - *La deformazione gravitativa profonda di Rosone in Valle dell'Orco.* Boll. Soc. Geol. It., 108, 401-408.

SAITO M. (1969) - *Forecasting time of slope failure by tertiary creep.* Proc. 7th Int. Conf. Issmfe, 2, 677-683.

SAVAGE W.Z. (1993) - *Gravity-induced stresses near a vertical cliff.* Int. Journ. Rock Mech. Min. Sc., 30 (5), 325-330.

SAVAGE W.Z. (1994) - *Gravity induced stresses in finite slopes.* Int. Journ. Rock Mech. Min. Sc., 31 (5), 471-483.

SAVAGE W.Z. & SMITH W.K. (1986) - *A model for the plastic flow of landslides.* US Geol. Surv., Prof. Paper 1385, 32 pp.

SAVAGE W.Z. & VARNES D.J. (1987) - *Mechanics of gravitational spreading of steep-sides ridges (sackung).* Iaeg Bull., 3 (5), 31-36.

SKEMPTON A.V. & HUTCHINSON J.N. (1969) - *Stability of natural slopes and embankment foundations. State of art report.* 7th Conf. Soil Mech. Found. Eng., Mexico, 291-335.

SORRISO-VALVO M. (1984) - *Un caso di deformazione gravitativa profonda nel bacino della fiumara di Plati (Reggio Calabria).* Boll. Soc. Geol. It., 103, 701-706.

SORRISO-VALVO M. (1995) - *Considerazioni sul limite tra deformazione gravitativa profonda di versante e frana.* Mem. Soc. Geol. It., 50, 179-185.

STINI J. (1941) - *Unsere Taler.Wachsen zu.* Geol. Bauwes, 13, 71-79.

STINI J. (1952) - *Neuere Ansichten uber «Bodenbewegungen» uber Beherrschung durch den Ingenieur.* Geol. Bauwes, 19 (1), 31-54.

SWOLF H.S. & SAVAGE W.Z. (1986) - *Topographic modification of in situ stress in extensional and compressional tectonic environments.* Proc. Int. Symp. Rock Stress Rock Stress Measur., 89-98.

TABOR R.W. (1971) - *Origin of ridge-top depressions by large-scale creep in the Olimpic Mountains.* Bull. Soc. Geol. Am., 82, 1811-1822.

TER-STEPANIAN G. (1966) - *Type of depth creep of slopes in rock masses.* Probl. Geomech., 3, 49-69.

VARNES D.J. (1978) - *Slope movements. Types and processes.* In: Schuster & Krizker (eds) «Landslides: analysis and control». Spec.Rep. 176, Transp. Res. Board, Nat. Ac. Sc., Washington.

VARNES D.J., RADBRUCH-HALL D. & SAVAGE W.Z. (1989) - *Topographic and structural conditions in areas of gravitational spreading of ridges in the western United States.* U.S. Geol. Surv. Prof. Paper 1496, Washington, p. 1-28.

VOIGHT B. (1988) - *A method for the prediction of volcanic eruptions.* Nature, 332, 125-130.

VOIGHT B. (1989) - *A relation to describe rate-dependent material failure.* Science, 243, 200-203.

ZARUBA Q. (1969) - *Deformace hornin vznikle vytlacovanim podlozi (Superficial quasi-plastic deformations of rocks).* Rozpravy Csav, 15, 66 Series MPV, Praha.

ZARUBA Q. & MENCL V. (1969) - *Landslides and their control.* Elsevier, Amsterdam. Academia- Praha.

ZARUBA Q. & MENCL V. (1976) - *Engineering geology.* Devel. in Geotech. Engin. 10, 14, Elsevier, Amsterdam, 504 pp.

ZISCHINSKY U. (1966) - *On the deformation of high slopes.* Proc. lst Conf. Int. Soc. Rock Mech., Lisbon, Sect. 2-, 179-185.

ZISCHINSKY U. (1969 a) - *Uber Sackungen.* Rock Mech., 1(1), 30-52.

ZISCHINSKY U. (1969 b) - *Uber BergzerreiBung und Talzuschub.* Geol. Rund., 58(3), 974-983.

ZISCHINSKY U. (1969 c) - *Rheologie und Felsmechanik aus geologischer Scist.*. Rock Mech., Suppl. V, 21-32.