Analysis of the Landslide Movements

Ancuța Rotaru, Daniel Oajdea and Paulică Răileanu

***Abstract*—**Understanding the causes of slope development, particularly the initiation of movement, requires knowledge of a set of factors, usually associated with groundwater, that are often difficult to determine. Landslides commonly occur as a result of: heavy rainfall, rapid snowmelt, wet winter and spring particularly if previous years were also wet, the removing of the material from the base, loads material at the top, earthquakes, erosion, poor forest management, addition of water to a slope from irrigation, roof downspouts, poor drainage, septic-tank effluent, canal leakage, or broken water. Most landslides in Romania occur as a result of a combination of poor forest management and intense rainfall. A continuous recording of landslide displacements is often required in order to better understand the complex relationship between the triggering factors and the dynamics of the movement. In recent years structural geology has been used as a tool to investigate the development and evolution of potential rockslides. The recognition of the processes that triggered the movement is of primary importance to understand the landslide mechanisms. The paper analyses the movement of the landslides from the point of view of different stages of landslide activity: pre-failure stage, failure sage, post-failure stage and reactivation stage.

***Keywords*—**failure stage, landslide activity, reactivation stage, triggering conditions

I. Introduction

The landslides represent a serious problem almost in all parts of the world, because they cause economic or social losses on private and public properties.

Natural disasters have demonstrated the destructive power of sudden mass movements during a landslide, which continue to claim lives and cause substantial damage to property and infrastructure on an annual basis [1]. Despite frequent occurrence of such natural hazards, considerable gaps remain in basic understanding and modelling of key triggering mechanisms and the spatial extension of scars and deposition zones, hence hindering efforts to develop effective early warning systems and establish indicators for incipient failure and any subsequent damage [2].

In Romania landslides are priority hazards because represent a high risk. Many recent landslides have been reported as occurring in Romania in conjunction with recent major floods and poor forest management. That's why the attention of Romanian researchers in the field of natural hazards is made for landslides analysis. It is necessary to emphasize that the term landslide is used in a general sense to describe all types of gravitational movements of earth material. Nevertheless, landslides can be classified according to variety of types and velocities of movement.

The term landslide denotes "the movement of a mass of rocks, earth or debris down a slope" [5]. Landsliding is either a natural process or it occurs as a result of human activities which disturb the slope stability. These phenomena differ according to their shape, size of the displaced mass, moving mechanisms, velocity and other characteristics.

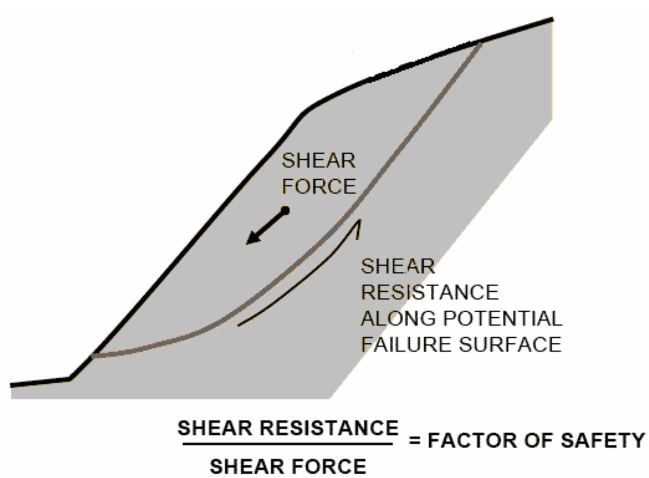

Fig. 1 Shear resistance vs. shear force during a landslide movement

They can occur on any terrain given the right conditions of soil, moisture, and the angle of slope. Part of the natural process of the earth's surface geology, landslide serves to redistribute soil and sediments in a process that can be in abrupt collapses or in slow gradual slides.

Some features might be noticed before major landslides: springs, seeps, or saturated ground in areas that have not typically been wet before, new cracks or unusual bulges in the ground, street pavements or sidewalks, soil moving away from foundations, ancillary structures such as decks and patios tilting and/or moving relative to the main house, tilting or cracking of concrete floors and foundations, broken water lines and other underground utilities, leaning telephone poles, trees, retaining walls or fences, offset fence lines, sunken or down-dropped road beds, sudden decrease in creek water

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levels when rain is still falling or just recently stopped, sticking doors and windows, and visible open spaces indicating jambs and frames out of plumb [6].

Slope movements can take very different configurations from rock topple to mudflow, can involve a variety of materials from hard rock to sensitive clay and loess, and can result from a variety of phenomena from rapid snowmelt or heavy rainfall to earthquakes.

Because the factors affecting landslides can be geophysical or human-made, they can occur in developed areas, undeveloped areas, or any area where the terrain was altered for roads, houses, utilities or buildings [4], [7].

The areas that are generally prone to landslides are: on existing landslides, old or recent, on or at the base or top of slopes, in or at the base of minor drainage hollows, at the base or top of an old fill slope, at the base or top of a steep cut slope.

The areas that are generally safe from landslides are: on hard, non-jointed bedrock that has not moved in the past, on relatively flat-lying areas away from slopes and steep river banks, at the top or along the nose of ridges, set back from the tops of slopes.

II. Movements of a landslide

There are three main factors that control the type and rate of mass wasting that might occur at the Earth's surface [29]:

(i) Slope gradient: The steeper the slope of the land, the more likely that mass wasting will occur.

(ii) Slope consolidation: Sediments and fractured or poorly cemented rocks and sediments are weak and more prone to mass wasting.

(iii) Water: If slope materials are saturated with water, they may lose cohesion and flow easily.

The motion of the heterogeneous mass containing water (snow), soil material and rocks is complicated and does no resemble the flow of a homogeneous and Newtonian fluid.

There are four possible different stages of landslide activity [2, 4]:

(i) Pre-failure stage, when the soil mass is still continuous. This stage is mostly controlled by progressive failure and creep;

(ii) Failure stage, characterized by the formation of a continuous shear surface through the entire soil or rock mass;

(iii) Post-failure stage which includes movement of the soil or rock mass involved in the landslide, from just after failure until it essentially stops;

(iv) Reactivation stage when the soil or rock mass slides along one or several pre-existing shear surfaces. This reactivation can be occasional or continuous with seasonal variations of the rate of movement.

Many types of warning systems have been proposed and the selection of an appropriate one should take into account the stage of landslide activity: pre-failure, failure, or post-failure stage.

At pre-failure stage, a warning system can be applied either to revealing factors or to aggravating factors. The revealing factors can be the opening of fissures or the movement of given points on the slope. The warning criterion will be the magnitude or rate of movement. When the warning system is associated to aggravating factors, we have to define the relation between the magnitude of the controlling factors and the stability condition and the rate of movement of the slope. The warning criterion can be: the pore water pressure, the stage of erosion, the minimum negative pore pressure or rainfall [13].

For the post-failure stage, the hazard associated to a given rate of movement is governed by the materials involved and the predisposition factors, and thus it is more difficult to be defined.

At failure stage, the warning system can be linked to revealing factors, generally a sudden acceleration of movements or the disappearance of a target [21].

At post-failure stage, a warning system has to be associated to the expected consequences of the movement. It is generally associated with the rate of movement and run out distance.

Warning systems do not modify the hazard but contribute to reducing the consequences of the landslide and thus the risk, in particular the risk associated to the loss of life [21].

III. Dynamics of landslide activity

The conditions necessary for the origin of landslides are: (1) geological and lithological slope structure corresponding to a two-layered medium with a brittle upper layer and a plastic lower layer; sufficient thickness of the upper layer in order to transfer loads to the lower one, which generate irreversible deformations in the latter, and to form blocks; (2) conditions for plastic deformations and lateral spreading of masses of the lower layer. These conditions serve as criteria for the forecasting of the locations of block landslides [11]. The determined low speeds of contemporary movements of the block landslides provide the possibility to use the affected territories for construction and other economic activity [10].

The dynamic of the landslide is composed of one or more possible movements representing one or more stages of landslide activity. These movements are analyzed below.

A. *Movements preceding a slide*

Certain slides occurred without warning. No slide can take place unless the ratio between the average shearing resistance of the ground and the average shearing stresses on the potential surface of sliding has previously decreased from an initial value greater than one to unity at the instant of the slide [28]. The only landslides that are preceded by an almost instantaneous decrease of this ratio are those due to earthquakes and to spontaneous liquefaction. All the others are preceded by a gradual decrease of the ratio, which involves a progressive deformation of the slice of material located above the potential surface of sliding and a downward movement of all points located on the surface of the slice.

Preparatory processes make the slope susceptible to movement without actually initiating it and thereby tending to place the slope in a marginally stable state. Triggering processes initiate movement. If a landslide comes as a surprise, we could say that the observers failed to detect the phenomena that preceded the slide. A good understanding of the landslide's triggering is very important. A summary of landslide triggering conditions, natural and human, is given in Table 1. These factors shift the slope from a marginally stable to an actively unstable state.

Removal of support: Excavation or erosion at the base of a slope can cause an unstable situation. The removed material was supporting the soil directly upslope from the disturbed area. This loss of support can trigger landslides.

Removal of vegetation: To reduce landslide incidence, (i) the vegetation removes water from the soil; and, (ii) the root systems support the soil and provide a stabilizing effect. Areas that experience forest fire or clear-cut timbering are subject to landslides for many years after the accident.

Addition of moisture: Any soils, especially clays, are hard when dry but transform into soft mud when water is added. The addition of water reduces the shear strength of the soil and can develop landslides and is the most common source of landslide problems.

Addition of weight: Adding weight to the top of a slope can generate landslides if the added weight exceeds the shear strength or increases the pore pressure of the soils below.

Oversteepening: The angle of repose is the maximum angle that a material can be stacked and remain stable. If soil is piled up at an angle that exceeds the angle of repose, landslides can result.

TABLE 1 LANDSLIDE TRIGGERING CONDITIONS

Landslide triggers	Natural triggers	Human triggers
Removal of support	erosion at the base of a slope by streams, waves, glaciers	excavation at the base of a slope or excavation on a hillside
Removal of vegetation	forest fires	timbering
Addition of moisture	rainfall or snowmelt	sewage or runoff disposal, broken water pipes, improper grading
Addition of weight	heavy snowfall, volcanic ash, landslides	placement of fill
Over-steepening	(this term is used as "removal of support")	placing fill at a gradient that exceeds the angle of repose
Vibrations	earthquakes, nearby landslides	blasting, operation of heavy equipment

Vibrations: Sudden movements can cause the particles in a soil to lose contact with one another. Thus, the frictional forces that enable that material to remain on a slope are lost and landslides can be triggered. Vibrations from earthquakes and heavy equipments trigger landslides.

Often the large amount of groundwater, and excess hydrostatic pressures, caused considerable pot-holing to occur before the slope commenced to move [12]. It is likely that such hydrostatic pressures are transmitted down-slope, through natural pipe networks, and have some influence on the gradual creep movement that occurs on the majority of such slopes.

Very gradual ground shifts are known to precede major landslides. Often these are on a scale of millimeters – too slight to even be noticed by local observers, but enough to be detected via satellite using radar interferometry [8].

The total displacement just before failure is dependent on the strain that corresponds to the peak strength and on the thickness of the failure area. The total movement is smaller for normally consolidated clay than for stiff overconsolidated clay [18].

B. *Movements during the slide*

Shear failures, along a surface of sliding through any material, are associated with a decrease of the shearing resistance. Therefore, during the first phase of the slide, the sliding masses advance at an accelerated rate. However, as the slide proceeds, the force that tends to maintain the sliding movement decreases, because the mass comes into more and more stable positions. Therefore the accelerated movement changes into a retarded one, and finally it stops or assumes the character of creep.

The maximum velocity of the movement depends on the average slope angle of the surface of sliding, the importance of the effect of the slip on the resistance against sliding, the nature of the stratification, the orientation of the stratification.

The slope angle is the angle between the horizontal and the ground surface. Landslides on slopes with low slope angles highlight the role clay layers within the shale formations action in slope stability.

Landslides are more likely to occur on slopes with slope lines to the north (north-facing slopes). The hypothesis is that less direct sunlight and slightly cooler temperatures lead to less evaporation and more moisture in the soils on north-facing slopes.

Based on their velocity, landslides can be divided into seven classes. Table 2 summarizes the velocity scale and the associated destructive significance.

The steepest surfaces of sliding develop in fairly homogeneous materials, such as irregularly jointed rocks, cemented sands, and loess, which combine cohesion with high internal friction. Therefore slides in such materials are likely to be sudden.

Velocity is the most important parameter determining the destructive potential of landslides. "Catastrophic" velocities of the order of several meters per second are attained only by certain types of landslides. High velocities are the consequence of a range of strength loss mechanisms. Strength loss can occur instantly during the process of failure, through loss of cohesion, liquefaction of granular material or remoulding of sensitive clay. Further important loss of strength can occur during movement, including rock joint roughness reduction, shearing in clays, sliding surface liquefaction, frictional heating, loss of internal coherence of the sliding body, material entrainment, rapid undrained loading, and entrainment of water. Extremely rapid landslides include rock, debris and earth fall, rock block topple, rock slide, debris slide, flow slide in granular soil or clay, debris avalanche, debris flow and rock avalanche. There is a need to study the post-failure behavior of materials, in order to facilitate predictions of the behavior of extremely rapid landslides for hazard assessment.

Observed failure phenomena in rainfall-induced landslides showed that the failure mode depends greatly on the grain size. The flow behaviour of soils with 20% and 30% loess is different from the sands or a mixture with 10% loess, showing greater velocity without deceleration. This suggests the existence of a mechanism that maintains high pore pressures during motion for these soils.

TABLE 2 CLASSIFICATION OF LANDSLIDES AFTER VELOCITY

Landslide velocity	Destructive significance
< 1.6mm/yr	Imperceptible without instruments. Construction possible with precautions.
16mm/yr to 1.6m/yr	Permanent structures undamaged by movement.
1.6m/yr to 13m/mon	Remedial construction can be undertaken during movement. Insensitive structures can be maintained.
13m/mon to 1.8m/h	Some insensitive structures can be temporarily maintained.
1.8m/h to 3m/min	Escape evacuation possible. Structures and equipments destroyed.
3m/min to 5m/s	Some lives lost because not all persons are able to escape.
> 5 m/s	Catastrophe of major violence. Buildings destroyed by impact of displaced material. Many deaths.

In saturated soils, during motion, the pore pressure of the saturated mixture increased with velocity because of the floating of sand grains that accompanied the movement for each test [12]. The sample with finer grain sizes or greater fine-particle (loess) contents floated more easily, and high pore pressure could be maintained during motion. The floating ratios of grains reached a high value (>0. 85) at a very slow velocity for samples with 20% and 30% loess. It is concluded that grain size and fine-particle contents can have a significant impact on the mobility of rainfall-induced landslides [13].

The decrease of the shearing resistance produced by the slip ranges between 20 percent for fairly loose sands and clays with low sensitivity and probably 90 percent for very loose, saturated sands, silts or soft extrasensitive clays. Slides in very sensitive clays and loose, saturated sand occur very rapidly.

The weight of standing water puts hydrostatic pressure on a structure. The deeper the water, the more it weighs and the greater the hydrostatic pressure. If a slide occurs on account of an excess hydrostatic pressure at the horizontal boundary between sand or silt and clay, the maximum velocity of the movement is likely to be very high even if the surface of sliding is horizontal.

By contrast, slides due to an increase of the shearing stresses on a potential surface of sliding in more or less homogeneous masses of residual soil or of clay with low sensitivity seldom attain a velocity of more than 0.30 cm per minute, and the velocity may be as low as 0.30 cm per hour [14], [20].

The type of movement is dependent on many factors including the slope gradient, type of material, and the hydrological conditions [12].

There are six distinct types of landslide movement: fall,

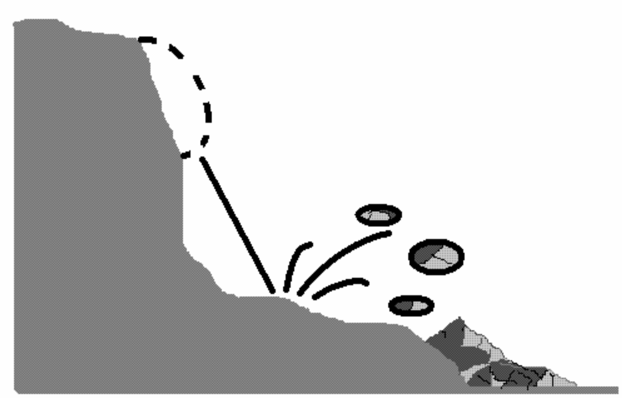

Fig. 2 Fall

topple, slide, spread, flow, and complex.

1) Falls

Falls are abrupt movements of masses of geologic materials, such as rocks and boulders. A fall starts with the detachment of soil or rock from a steep slope along a surface on which little or no shear displacement take place. The material then descends mainly through the air by falling, bouncing, or rolling. Separation occurs along discontinuities such as fractures, joints, and bedding planes and movement occurs by free-fall, bouncing, and rolling.

The material may roll for considerable distances downslope forming talus slopes. Movement is very rapid to extremely rapid, with no prior indication. Except when the displaced mass has been undercut, falling will be preceded by small sliding or toppling movements that separate the displacing material from the undisturbed mass. Falls are strongly influenced by gravity, mechanical weathering, and the presence of interstitial water. They are very common, both in rock and debris, on steep slopes below bedrock scarps in upland areas. Falls may be activated due to a loss of support because of basal erosion, undercutting, to a loss of internal strength due to weathering, or to mechanical break-up by water freezing/thawing processes (temperature variations), or high water pressures.

Falls occur in almost all types of rocks, especially along bedding planes, joints or local fault areas, or fault planes.

There are no reliable methods for calculating the stability of a slope with respect to falls.

Soil falls may occur when an easily erodible material (clean sand or silt) underlies a more erosion-resistant material (overconsolidated clay).

Falls are one of the main erosion mechanisms in heavily overconsolidated clays [12].

In Romania, in the alpine belt of the Carpathian Mountains, rockfalls are the most common mass movements. These processes are most common in the crystalline rocks on the steep slopes of glacial cirques and valleys.

2) Topples

A topple is the forward rotation out of the slope of a mass of soil or rock about a point or axis below the center of gravity of the displaced mass. The rock mass may stay in place in this position for a long time or it may fall away down-slope due to further weakening or undercutting. This will depend on the rock type, the geometry of the rock mass, and the extent of the discontinuities.

Topples range from extremely slow to extremely rapid, sometimes accelerating throughout the movement.

3) Slides

Slides involve the displacement of masses of material along well-defined surfaces of rupture called slip or shear surfaces. The material moves in mass but is likely to break up with distance from the initial rupture point.

A slide is a down-slope movement of a soil or rock mass that occurs dominantly on surface of rupture or on relatively thin zones of intense shear strain [26].

Often the first signs of ground movement are cracks in the original ground surface along which the main scarp of the slide will form. The displaced mass may slide beyond the toe of the surface of rupture covering the original ground surface of the slope, which then becomes a surface of separation.

Whenever a mass of slope material moves as a coherent block, a slide has taken place. There are several types of slides, but one of the most common is a slump. A slump occurs when a portion of hillside moves downslope under the influence of gravity. A slump has a characteristic shape, with a scarp or cliff at the top of the slump, and a bulge of material (often called the toe of the slump) at the base of the slump.

Slides are divided into rotational and translational slides.

Rotational and translational landslides are movements above one or more failure surfaces. The movement occurs as a result of either sliding on discrete shear surfaces or ductile deformation within a shear zone. One of two movement styles is evident during accelerating phases for all landslides observed. The first style has a linear form in a plot of $1/v$ against time (v is velocity). The second style has an asymptotic form in the same plot, trending toward steady-state movement rates. The linear form occurs in landslides in which crack propagation (shear surface generation) is the dominant process, whereas the second style occurs where movement is taking place across existing planes of weakness or as a result of ductile deformation processes [15], [28].

a) Rotational slides

Rotational slides involve sliding on a shear surface which is concave upwards in the direction of movement where the displaced mass rotates about an axis which is parallel to the slope. The back of the slide is marked by a crack or scarp

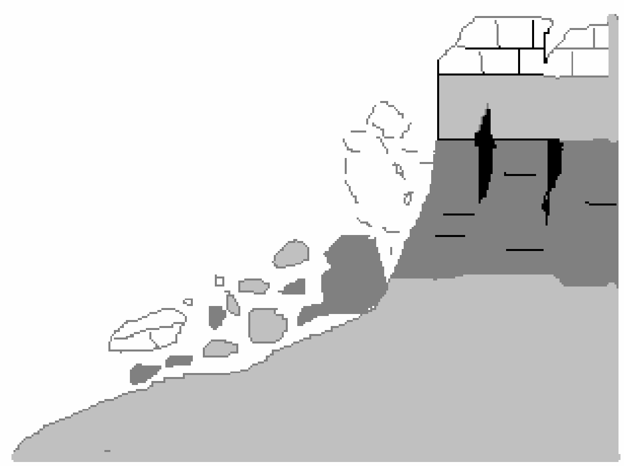

Fig. 3 Topple

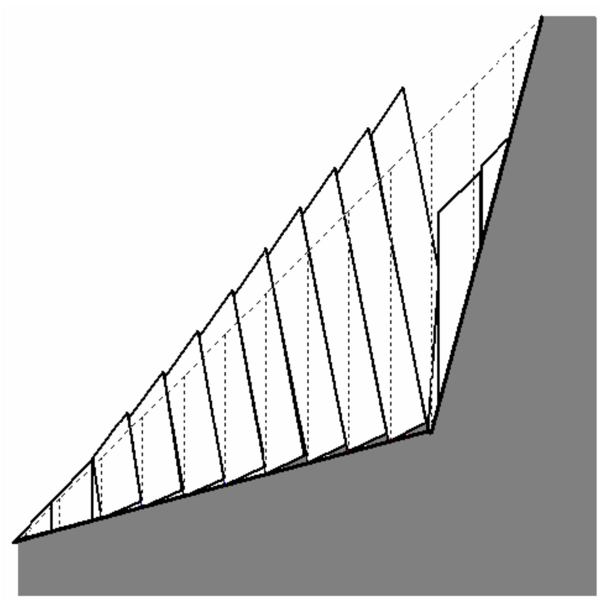

Fig. 4 Movement along a circular failure surface of a topple: transition

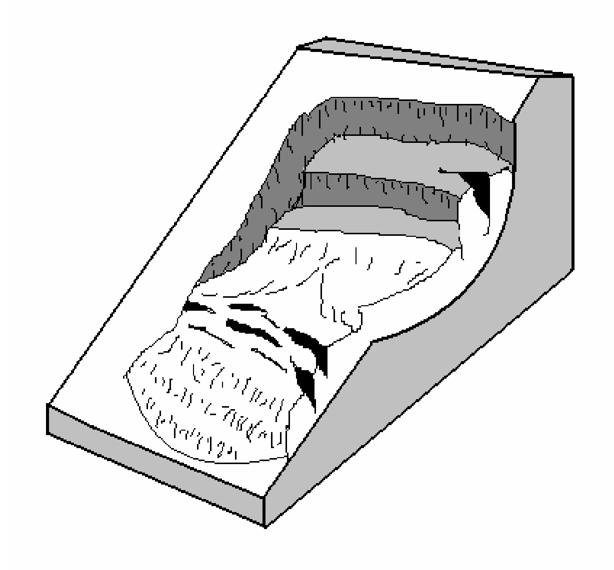

Fig. 5 Rotational slide

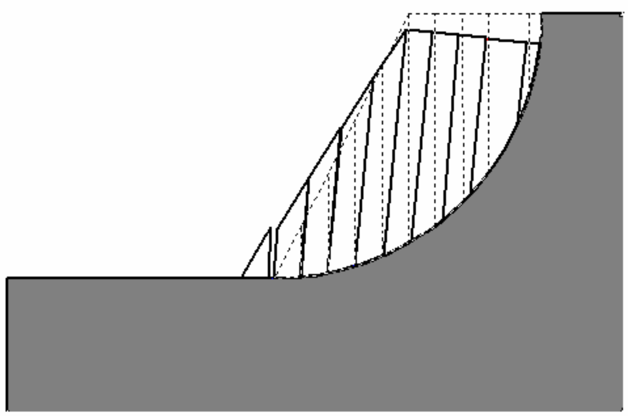

Fig. 6 Movement along a circular failure surface of a slide: rotation

slope which is concentric in plan. The displaced mass may flow further down-slope beyond the rupture surface to form a zone of accumulation at the toe of the total feature. Rotational slides can be single events or multiple events [15].

b) Transitional slides

Transitional slides are also called planar slides. The mass of material moves down-slope on a largely planar surface. Translational slides can have very different impacts to rotational slides. Where the slope is sufficiently steep and the shearing resistance along the slip surface remains low, the movement can continue on for a long distance, being different to rotational slides. Translational slides in rock usually occur along discontinuities such as bedding planes or joints. In the case of debris slides failure can occur on shallow shear surfaces at or near the base of the surface materials where there can be marked changes in strength and permeability.

Slopes where the discontinuities lie parallel to the ground

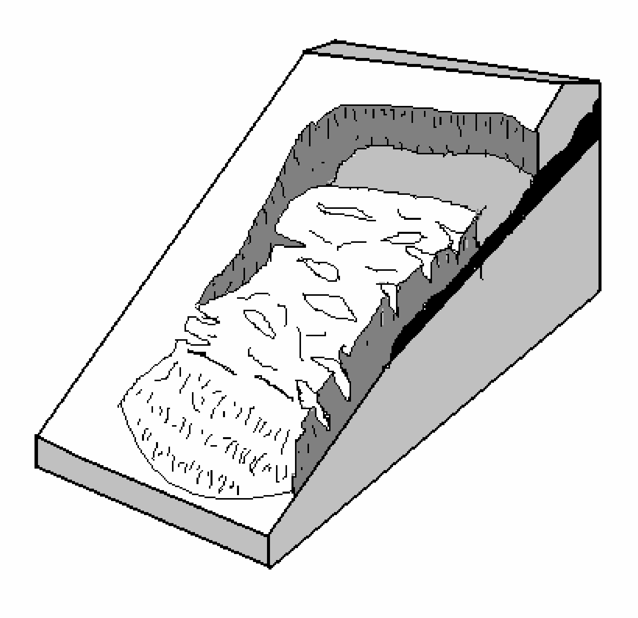

Fig. 7 Transitional slide

surface would be more prone to translational sliding [15].

4) Spread

Spread is defined as an extension of a cohesive soil or rock mass combined with a general subsidence of the fractured mass of cohesive material into softer underlying material. Spread may result from liquefaction or flow of the softer material.

Spreads are distinctive because they usually occur on very gentle slopes or flat terrain.

The dominant movement in spreads involves the lateral extension of the underlying weak material (soil or bedrock) due to shearing or tensional fractures. It can be caused by liquefaction or plastic flow.

Failure is usually triggered by rapid ground motion, such as that experienced during an earthquake, but can also be artificially induced.

The resulting lateral movement breaks up the overlying material into more or less independent units or lumps that may subside, translate, rotate, or disintegrate.

This extension of coherent rock or soil may be due to plastic flow of a weaker subjacent layer. The coherent mass may subside into the layer or it may slide or flow.

Spreading in fine-grained materials on shallow slopes is usually progressive. The failure starts suddenly in a small area and spreads rapidly.

5) Flows

A flow is a spatially continuous movement in which surfaces of shear are short-lived, closely spaced, and usually not preserved. The distribution of velocities in the displacing mass resembles that in a viscous liquid. The lower boundary of the displaced mass may be a surface along which appreciable differential movement has taken place or a thick zone of distributed shear. Thus there is a gradation from slides to flows depending on water content, mobility, and evolution of the movement [21].

Flows can occur in bedrock but they are extremely slow and occur in areas of high relief. Flows in unconsolidated materials are much more obvious.

During a flow the material breaks up as it moves down a slope and flows as a viscous fluid.

The rate of movement can range from very slow to extremely rapid, and in terms of moisture content, can range from totally saturated to dry. The effect of water is important in initiating flow.

There are some different types of flows: rock flow, eathflows, debris flow, mudflow, spontaneous liquefaction, and solifluction.

a) Rockflow

Rockflow involves gradual deformation of the rock mass along joints and fractures. There is no distinct failure plane. The movements are extremely slow and constant with time. This type of movement is mostly referred to as creep. Flow movements may result in folding, bending, bulging, or other manifestations of plastic behaviour [25].

In Romania the rockfall area on steep slopes comprised folded and faulted Paleocene sandstones in the Eastern Carparthians. Rockfalls in the Buzau Mountains (Eastern Carpathians) resulted from the March 4, 1977, earthquake (M = 7.2). The volume of rock displaced by the earthquake was 20 - 50 times larger than the average annual volume emanating from the cliffs from other causes.

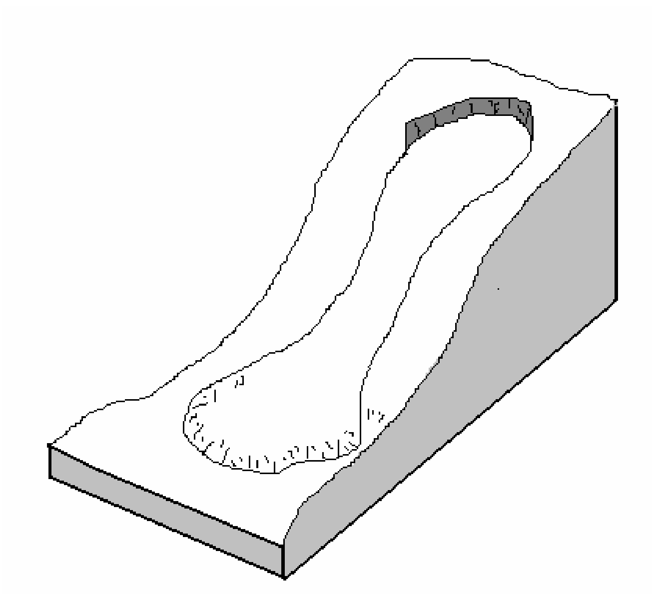

Fig. 8 Earthflow

b) Earthflow

Earthflow represents a transition between a slide and a mudflow [19]. Earthflows are viscous fluid flows. The flow mass can be wet or dry. Slip surfaces within the moving mass are not visible. The boundary between the moving mass and the material in place may be a distinct surface or it may be a relatively thick area. The slope material liquefies and runs out, forming a depression at the head. The flow is elongate and usually occurs in fine-grained materials or clay-bearing rocks on moderate slopes and under saturated conditions.

Many earthflows continue to move for many years until the inclinations of the shear strength is insufficient.

c) Debris flow

Debris flow is a form of rapid mass movement in which a combination of loose soil, rock, organic matter, air, and water mobilize as slurry that flow downslope. Debris flows contain a high percentage of coarse fragments (<50% fines) and often result from unusually high precipitation or rapid snowmelt, that erodes and mobilizes loose soil or rock on steep slopes. The moving soil and rock debris quickly gains the capacity to move considerable amounts of material at faster and faster speeds. They often follow already existing stream channels and can extend for several kilometers before stopping and dropping their debris load in river valleys or at the base of steep slopes.

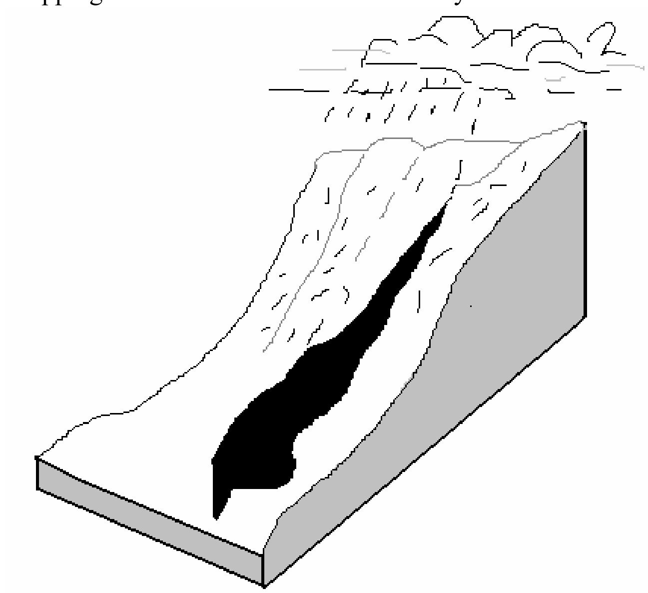

Fig. 9 Debris flow

Debris flows commonly mobilize from other types of landslides that occur on steep slopes, are nearly saturated, and consist of a large proportion of silt- and sand-sized material. Debris flows develop in arid and semiarid regions where the ground is not covered by vegetation or in slopes filled with debris. Fires that denude slopes of vegetation intensify the susceptibility of slopes to debris flows [22].

d) Mudflow

Mudflow or mudslide is the most rapid (up to 80 km/h / 50 mph) and fluid type of downhill mass wasting. A mudflow is an earthflow consisting of material that is wet enough to flow rapidly.

Mudflow occurs on steep slopes over 10°. It's a rapid sudden movement which occurs after periods of heavy rain. When there is not enough vegetation to hold the soil in place, saturated soil flows over impermeable sub soil, causing great devastation and endangering lives.

Mud flows are made up of fine grained materials (>50% sand-, silt-, clay – sized particles [12]. They are highly saturated and can propagate very quickly.

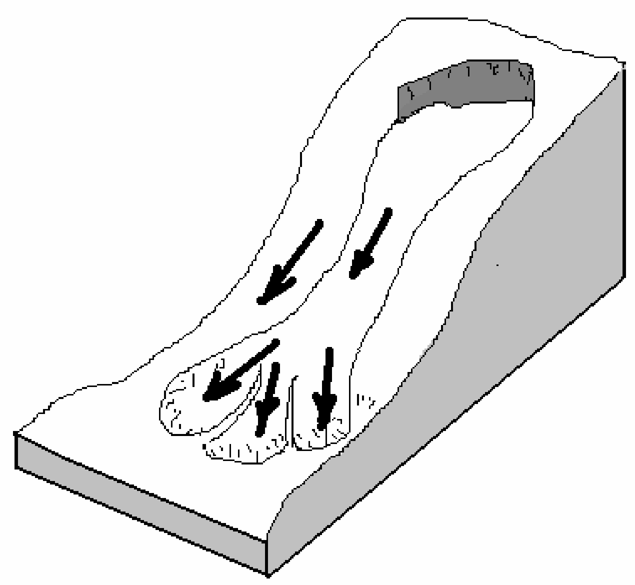

Fig. 10 Mudflow

6) Complex landslides

Complex landslides involve more than one type of movement mechanism. There can be different types of movement in different parts of the moving mass at the same time or a change of movement type as the landslide develops and proceeds down-slope. Though individual types can be identified in nature, two or more types of movement are often involved. A common occurrence is where slides develop into flows in the lower parts of the slope. Large landslide zones usually have complex landslide types.

TABLE 3 TYPES OF LANDSLIDES AFTER VARNES 1978, WITH THE MODIFICATIONS MADE BY CRUDEN AND VARNES IN 1996

Type of movement	Type of material		
	Bedrock	Type of soil	
		Coarse	Fine
Fall	Rock fall	Debris fall	Earth fall
Topple	Rock topple	Debris slide	Earth slide
Slide	Rock slide	Debris slide	Earth slide
Spread	Rock spread	Debris spread	Earth spread
Flow	Rock flow (deep creep)	Debris flow (soil creep)	Earth flow (soil creep)
Complex	Combination of two or more principal types of movement		

The experts recognizes the existence of complex landslides where ground displacement is achieved by more than one type of mass movement and emphasizes that this should not be confused with landslide complex, which is an area of instability within which occur many different types of mass movement.

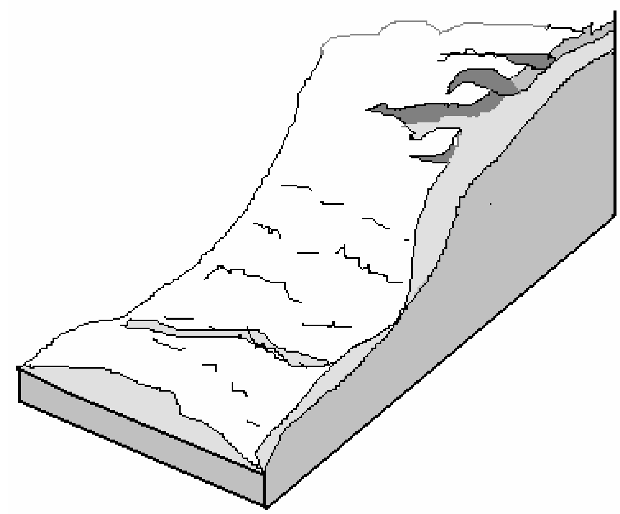

Fig. 11 Creep

In a complex landslide the materials can be divided in: rock, debris and earth. In reality there is a continuum of mass movements from falls through slides to flows. It is difficult to determine whether masses of material fell or slid, and there are instances where material both slid and flowed.

In Romania, mass movements are a significant hazard in the hilly and mountainous regions, particularly those underlain by flysch deposits. These deposits are complexes of folded and faulted sedimentary rocks containing marls, clays, shales, sandstones, and conglomerates. The distribution of mass movements in these deposits is controlled by various climatic, tectonic, and lithologic factors influenced by land-management practices. There are significant regional differences among types of mass movements, the quantities of materials delivered from the slopes into adjacent stream channels, and risks to various human activities.

In the Subcarpathians, formed predominantly of folded and faulted molasse deposits, slopes may be highly unstable. The instability is most frequently manifested by shallow (sheet) slides, landslides of medium depth, and mudflows typically 300-700 meters in length. The areas most affected by these features lie within the curvature subcarpathians in the Vrancea Seismic Region [24].

In the Eastern Carpathians, formed predominantly of Cretaceous and Paleocene flysch deposits, periglacial or immediate postglacial colluvial materials are major sources of mass movements. These deposits generally range from 10 to 30 meters in depth, and landslides within them are commonly activated or reactivated by regional deepening of the valley network in the long term, or deforestation practices by people. Because of their association with stream valleys, these landslides often affect towns, communication lines, and roads, and may partially or totally block valleys when they move. In the Moldlavian Plateau, the areas most affected by landslides occur on slopes built up of alternations of marls and clays, with intercalations of conglomerates and sandstones. In the Transylvanian Plateau deep landslides, called glimee, are commonly triggered by heavy rains.

C. Movements after slide

After the descent of the sliding mass has eliminated the differences between the driving and the resisting force, the movement passes into a slow creep, unless the slide has radically altered the physical properties of the sliding mass [23]. The change can be due either to mechanical mixture of the solid material with water or to a destruction of the intergranular bonds at unaltered water content of the material.

Soil creep is a very slow movement, occuring on very gentle slopes because of the way soil particles repeatedly expand and contract in wet and dry periods. When wet, soil particles increase in size and weight, and expand at right angles. When the soil dries out, it contracts vertically. As a result, the soil slowly moves downslope.

Extrasensitive clays are commonly very thixotropic.

If clay is very sensitive, a slide may turn it into a mass capable o flowing on a gently sloping base, whereas a similar slide in clay with low sensitivity merely produces a conspicuous local deformation. The change in consistency produced by the disturbance of sensitive clay is always associated with a change of the permeability.

Hence the strength of such clays is likely to increase considerably, at unaltered water content, after the clay has moved out of the slope.

If a slide causes the disintegration and breakdown of a mass of non-thixotropic sediments, such loess, during a period of heavy rainfalls, the slide material is likely to creep very actively for many years after the slide, and every new rainstorm accelerates the rate of creep [23].

D. Reactivation stage

It is considered that the creep phase of landslides is a preparatory stage of progressive failure and gives enough signals before turning into a catastrophic slope disaster.

The creep phase is reactivation of old landslides that took place in the long past due mainly to earthquake forces or tectonic activities through the faults. The formation of clay layers as a result of rock mineral weathering through the slip surfaces of the landslides justify the creep phase. The decomposition of rock minerals under the chemical action of underground water takes place through a previously developed plane of failure. After reaching a certain state of decomposition, the shear strength of the slip layer reduces considerably but not necessarily resulting in complete failure of the slope. The stress conditions along the slip surface lead to creep failure, in which the stresses do not change but shear deformations do occur under the constant high confining stresses.

An increase in rainfall could also lead to increased reactivation of ancient landslides. Each phase of reactivation is promoted by the occurrence of high groundwater levels [27].

If a slope has moved before, it has a higher chance of moving than a slope with similar characteristics that has never moved. Characteristics such as scarps, toes, and seeps hint old landslide activity. Building on the toe of an ancient slide that reactivates can be devastating if buildings and roads are built upon them. Once moving, many old landslides are difficult to stop. Movement can occur after many years of inactivity, so sites are never safe.

In Romania slopes affected by reactivation of landslides are locate in the Eastern Carpathians. Landslides occur in colluvial deposits 10-30 meters thick developed on Paleogene flysch. Oil production during the last years in the eastern part of Romania's Carpathian Mountains has added to the total number of drilling/production wells and led to such related activities as the construction of roads, platforms, and embankments. Other harmful human influences include heavy traffic, forest exploitation, messy water because of well drilling, vibration in soils and bedrock, and the removal of gravel deposits from the main river. Unfavorable natural conditions such as: nonuniformity in the slope lithology, high slope gradients, and high rainfall rates combined with these kinds of engineering works have accelerated local instability by increasing surface runoff and erosion. This has lowered the base level in the adjacent valleys/gullies by 1-2 meters, increasing the slide potential.

An example for the eastern part of Romania's Carpathian Mountains is the Zemes landslide, which extends over 1.4 - 1.8 kilometers in length, with a width of around 500 meters at the slope base and a total change in elevation of about 350 meters. This and similar slides cover 30-40 percent of the land on both sides of Tazlaul Sarat Valley. They have developed especially on soft or altered rocks and almost always involve the quaternary deposits (coarse altered materials in a clay matrix). Unfortunately, these recurrent landslides produce an asymmetric shape to the valley, which increases the potential for landslide reactivation because of infiltration of water into the ground [3].

Dormant landslides are difficult to recognize. They are covered by vegetation and characterized by trees and cracks that have been filled by debris. Dormant landslides can be activated by even small changes of the stability conditions (excavation at the toe of the slope). The age of a dormant landslide can be determined from the age of the oldest tree that is growing within the landslide area, from the stage of the erosion, and from the development of recent soil profiles. The slides that have been stabilized by chemical or mechanical means can be either active or dormant.

IV. Conclusion

A continuous recording of landslide movements is required in order to better understand the complex relationship between the triggering factors and the dynamics of the displacement.

The recognition of the processes that triggered the movement is of primary importance to understand the landslide mechanisms [9].

Climate change locally increases the intensity of rainfall raising the frequency of fast moving, shallow landslides. Intensification of land-use management amplifies the hazard. Population growth and expansion of settlements and

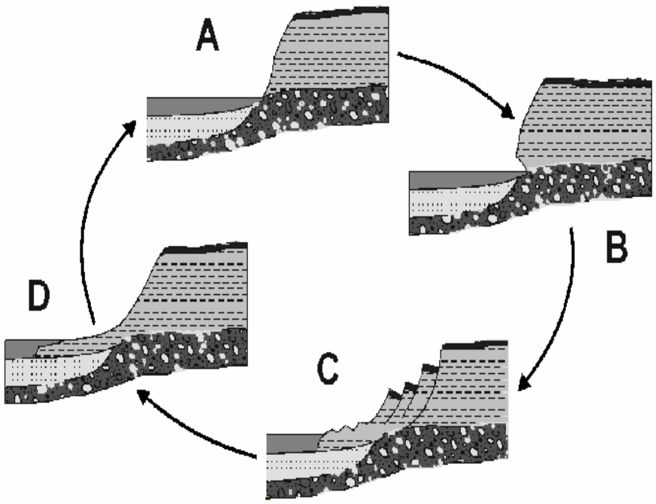

Fig. 12 Life cycle of a landslide

infrastructure over potentially hazardous areas have increased the impact of landslides.

These are only a few of landslides causes. We have to know a lot of them and, especially, we have to know the dynamic of a landslide surface and its history, because soils are vulnerable to all kinds of landslides [10].

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