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5.07 Mass-Movement Processes: Shallow Landslides

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Glossary

Complex landslide Landslide where two or more different types of movement occur in sequence.

Compound slide Slide where the rupture surface has two sections: steep circular or planar in the upper part and flatter planar in the lower part; there is a scarp at the top of the slide, graben and counterscarp with minor surface scarps further down the slide where it flattens out.

Landslide Deposits of rock, debris, and earth that have moved down a slope by gravitational forces.

Slump (rotational slide) Landslide movement along a curved rupture surface with little internal deformation of the mass.

Translational slide Landslide movement along a planar rupture surface and then moves out over the original ground surface.

5.07.1 Introduction

A landslide is a movement of a mass of rock, debris, or earth down a slope (Cruden, 1991). Several systems have been proposed in literature to classify landslides, but probably the most used system is that of Cruden and Varnes (1996) that emphasizes the type of movement and the type of affected material. This system is based on a former proposal by Varnes (1978) that combine three types of materials (rock, debris, and earth) with the five types of movements (fall, topple, slide, spread, and flow). This article concentrates on the shallow landslides, whereas the other related articles cover other types of landslides.

5.07.2 Definition and types of sliding

In the widely adopted landslide classification of Cruden and Varnes (1996), the term slide refers to a “downslope movement of a soil or rock mass occurring dominantly on surfaces of rupture or on relatively thin zones of intense shear strain” (Cruden and Varnes, 1996, p. 56).

Shallow landslides are one of the most common types of landslides in all the world's climate zones (van Asch et al., 1999) and are characterized by a reduced thickness, generally less than 5 m (Záruba and Mendl, 1982). In contrast to deep-seated landslides, shallow landslides are more controlled by local topography. In most cases shallow landslides involve loose materials and the interface to bedrock often constitutes the shear plane.

Shallow landslides can be grouped into two major groups based on the geometry of the rupture surface: rotational and translational slides. Varnes (1978) emphasized that characterizing the slide movement is important, i.e., rotational versus translational, because different stability analyses infer different failure mechanisms and choosing the wrong approach could give wrong interpretations.

Fig. 1 Examples of rotational and translational slides: (A) rotational earth slide; (B) translational earth block slide; and (C) debris slide. Reproduced from Varnes DJ (1978) Slope movement types and processes. In: Schuster RL and Krizek RJ (Eds.), *Special Report 176: Landslides: Analysis and Control*, pp. 11–33. Washington, DC: Transportation Research Board, National Research Council.

5.07.2.1 Rotational slides

Rotational slides occur along curved and concave surfaces of rupture (Fig. 1A). This circular rupture causes the displaced mass to move along the failure surface with little internal deformation. The upper part of the material moves almost vertically down while at the same time tilting backward the upper surface of the material (Cruden and Varnes, 1996). In comparison with other types of landslides, rotational slides are slow movements and in certain cases the pure rotational slides may self-stabilize due to the slides kinematic.

Rotational slides are commonly distinguished as single, multiple and successive slides (Fig. 2) (Hutchinson, 1968) according to a set of morphological features that can be identified in the field.

Single rotational slides (Figs. 3 and 4), commonly called slumps, are described by Varnes (1978) as a more or less rotational movement along a failure surface that is curved concavely upward. The failure surfaces can exhibit different geometries, such as spoon-shaped (Fig. 4A), but if the displaced mass extends along the slope perpendicular to the direction of the movement it may reach the shape of a sector of a cylinder whose axis is parallel to the slope (Fig. 4B).

Multiple rotational slides, which can be developed by the enlargement of a single rotational slide, display two or more sliding units whose failure surfaces intersect a common basal sliding surface (Buma and van Asch, 1996). If the slide is already degraded or vegetated and only the main scarp is observed, it might be difficult to distinguish between a multiple or a single rotational slide. A good example of the main morphological characteristics observed in the field can be seen in Fig. 5. This multiple shallow rotational slide triggered in the North of Lisbon (Portugal) shows one main scarp followed by two secondary scarps developed at a small distance from each other and in a stepped form. A discrete backward tilted head can be observed, as well as the cracks due to unloading of the scarp face induced by the settlement of the last slide. The movement along the flank induces a diagonal tension shear stress resulting in “en echelon” cracks. In the zone of bulging, the displaced mass moves over the toe of the failure surface, where lobes and radian tension cracks are evident.

The backward tilting usually developed on the main body of rotational slides allows for the water retention in the form of small ponds.

Fig. 2 Single (A), multiple (B), and successive (C) rotational slides. Adapted from Hutchinson JN (1988) General report: Morphological and geotechnical parameters of landslides in relation to geology and hydrogeology. In: Bonnard C (Ed.), *Proceedings of the Fifth International Symposium on Landslides*, pp. 3–35. Rotterdam, The Netherlands: A.A. Balkema; Buma J and van Asch T (1996) Slide (rotational). In: Dikau R, Brundsen D, Schrott L, and Ibsen M-L (Eds.), *Landslide Recognition: Identification, Movement and Causes*, pp. 43–61. Chichester: Wiley.

Fig. 3 Shallow rotational slide in North of Lisbon (Portugal). Note the cracks concentric in plan and concave toward the direction of movement.

Fig. 4 Shallow rotational slides in North of Lisbon (Portugal). Note the spoon-shaped geometry and the lobate form (A), as well as the cylinder-shaped geometry (B), which is the most common in this area, and the typical hummocky topography.

Successive rotational slides correspond to a series of rotational slides occurring one above the other (Skempton and Hutchinson, 1969) and affecting those above and below. The main difference between multiple and successive rotational slides, is that the latter do not share the same displaced mass nor the same failure surface.

A common way of describing landslides is to compare the ratio of the depth of the surface of rupture (D) to the length of the surface rupture (L). According to Skempton and Hutchinson (1969), most rotational slides have a D/L ratio between 0.15 and 0.30. The circular movement is generally controlled by the local geology, when the parent material is homogeneous, especially clay-rich soils (Cruden and Varnes, 1996). Because homogenous and isotropic materials are not common in nature, rotational slides are not as common as translational slides. Rotational slides are common in human-constructed slopes, which in many places are made of

Fig. 5 Shallow rotational slide in North of Lisbon (Portugal) and main morphological features observed in the field.

fill, a fairly homogeneous material. Rotational slides are also common above a flat-lying low permeable geological unit, such as a shale or clay layer. Water has a hard time passing through the lower layer, building up the pore water pressure above it and therefore producing the rotational failure with the bottom of the failure plane arc intersecting the lower layer.

5.07.2.2 Translational slides

In translational slides, the displaced mass moves out and downward along a planar or slightly undulating surface of rupture (Cruden and Varnes, 1996). The movement is strongly controlled by the presence of discontinuities such as faults, joints, bedding planes, or by the contact between weathered and unweathered material (Varnes, 1978; Cruden and Varnes, 1996).

Translational slides tend to be shallower and much longer on the slope than rotational slides (Fig. 6) and have D/L ratios < 0.1 (Skempton and Hutchinson, 1969). If the surface is highly inclined, the landslide may continue unchecked for long distances from the original site of movement. If the movement is not a long distance, the sliding mass may remain fairly intact as a block (Fig. 1B) and therefore, given the name of a block slide (Panet, 1969).

As the translational sliding continues, the displaced mass may break up more and more, especially if its velocity and water content is higher. These particular translational slides are sometimes called debris slides and can be seen in Fig. 1C.

The velocity of translational debris slides, as well as their propagation distance, increases with the slope angle and decreases with the clay content (Hutchinson, 1988). The displaced mass usually goes far beyond the sliding surface and speeds of up to 16 ms^{-1} having been recorded (Corominas, 1996). The loss of cohesion as well as the total or partial liquefaction of the material can lead to the development of debris flows (Hungr et al., 2014).

5.07.2.3 Compound slides

In some cases the slide is intermediate between a rotational slide and a translational slide and is called a compound slide (Cruden and Varnes, 1996) or a roto-translational slide (Fig. 7). The D/L ratios are also intermediate between the two types (Skempton and Hutchinson, 1969). Failure surfaces start with a steep scarp at the top and then flatten with depth. These slides generally have

Fig. 6 Shallow translation slides in São Miguel Island (Azores). Note the planar slip surface parallel to the ground surface and developed at the contact between the regolith cover and the bedrock.

Fig. 7 Compound slide (roto-translational) in North of Lisbon (Portugal). Note the movement starts with a typical rotational slide and evolves into a translational slide that hits the road further down.

Fig. 8 Compound slide in North of Lisbon (Portugal). Note the intermediate scarps and the graben formed within the displaced mass.

intermediate scarps (**Fig. 8**) that result from both internal deformation within the slide mass and shear along surfaces within the slide material ([Cruden and Varnes, 1996](#)). Grabens and counterscarps can result within the slide mass. In many cases this indicates a weak layer at the boundary between weathered and unweathered slide material. [Cruden et al. \(1991\)](#) found that the width of the graben may be proportional to the depth of the surface rupture.

5.07.2.4 Complex landslides

In other cases, the shallow landslide involves two or more different types of movements occurring in sequence (**Fig. 9**). When the displaced material first moves by slide and then flows, [Cruden and Varnes \(1996\)](#) recommended calling them complex slide flows. These movements are especially common in fine-grained and weak soils. The literature is filled with terms like mudslide and flow

Fig. 9 Complex landslide in North of Lisbon (Portugal). Note that the movement involves both sliding and then flowage.

slide to describe this type of complex landslide (Hutchinson, 1988), but Cruden and Varnes (1996) recommended that these terms not be used because they are confusing.

Recently, Hungr et al. (2014) revised the traditional Varnes classification (Varnes, 1978) and modified the definition of landslide-forming materials in order to make it compatible with geotechnical and geological terminology of rocks and soils. In the classification system proposed by Hungr et al. (2014), the slides in soil, often called soil slips, are classified as clay/silt rotational slide ("soil slump"), clay/silt planar slide, gravel/sand/debris slide and clay/silt compound slide.

5.07.3 Conditioning and triggering factors of shallow landslides

The conditions and processes that cause slope instability are multiple and frequently occur simultaneously. Therefore, trying to define which is responsible for a slope to become unstable is not only difficult, but may be inaccurate. In Earth Sciences, three types of factors are considered to influence the stability of the slope: predisposition factors, preparatory factors and triggering factors (Glade and Crozier, 2005).

The predisposition factors (e.g. lithology, slope angle) are static and related to the characteristics of the terrain, influencing not only the margin of stability but also acting as catalysts increasing the effectiveness of other dynamic factors (preparatory factors). The preparatory factors, together with the predisposition factors, decrease the margin of stability over time without being responsible for the beginning of the slope movement. These factors are of dynamic nature and may operate over long periods (e.g. strength reduction by weathering, tectonic uplift) or short periods (e.g. deforestation, erosion, anthropogenic activity).

The slope angle thresholds referred in the scientific literature for the initiation of shallow landslides varies according to the type of movement. Single, multiple and successive rotational slides occur on slopes ranging from 13 to 28 degrees (Skempton, 1953), 20.5 to 45 degrees (Brunsdén, 1974) and 8 to 30 degrees (Reiche, 1937; Reichelt, 1967; Hutchinson, 1988), respectively. Debris slides are usually triggered on slopes ranging from 25 to 45 degrees (e.g. Corominas, 1996; Hürlimann et al., 2016).

The lithology plays also a critical role on the occurrence of shallow landslides. The slopes most prone are those whose material generates an abundant amount of debris, when subjected to intense physical and chemical weathering (e.g. Abramson, 2002; Iversen, 2014). Additionally, in some regions of the planet, the intense seismic activity is a potentially generating process of loose deposits that easily mobilize in the presence of water (Fan et al., 2018).

The vegetation has a double-effect on slope stability. The mechanical effect is related to roots reinforcement that leads to an increase of the superficial soil shear strength (Schmidt et al., 2001; Van Beek et al., 2015). On the other hand, the hydrological effect is reflected in the loss of precipitation by canopy and litter layer interception as well as in the reduction of soil water moisture by evapotranspiration (Bogaard and Greco, 2016).

The triggering factors (e.g. short-duration intense rainfall, rapid snow melt, long-lasting rainfall, volcanic eruptions, seismic activity, slope undercutting) are also dynamic and responsible for the beginning of the slope movement by establishing the transition from a marginally stable to an actively unstable condition.

Instantaneous hydrological factors are the most common cause of slope instability. Shallow landslides are frequently triggered during single storms with durations of several hours to more than a day, which often exhibit a peak of intensity (Sidle and Bogaard, 2016). The soil water balance is essentially controlled by infiltration of precipitation, unsaturated percolation, and a rapid response of the groundwater to these single storms events (van Asch et al., 1999).

The shallow soils quickly respond to the regular change of wet and dry periods during which the percolation and evapotranspiration cause a vertical redistribution of soil water (van Asch et al., 1999). In such cases, failure is not necessarily determined by the development of positive pore-water pressures. On steep slopes, the decrease in apparent cohesion and the percolation of the wetting front are responsible for the reduction of soil shear strength (Dikau, 2013).

Considering that the increase in pore pressures is directly related to the depth of the slip surface, the amount of water that is required to trigger shallow landslides is not so demanding in comparison with the one that is necessary to trigger deep-seated landslides.

5.07.4 Shallow landslides: The mechanical behavior of natural slopes and the role of water

Natural slopes are systems where the forces that tend to promote the downslope movement are continuously in opposition to the forces that tend to resist the movement (Popescu, 2002).

The stability of a slope can be estimated through the Safety Factor (SF) whose formulation for translational slides is given by the ratio of resisting to driving forces acting parallel to the potential surface of rupture (Fig. 10). Thus, for translational slides,

$$SF = \frac{R}{D} \quad (1)$$

where R and D are the total resisting and driving forces.

Consequently, if the resisting force exceeds the driving force ($FS > 1$) the slope remains stable. On the contrary, if the resisting force is equal or lower than the driving force ($FS \leq 1$), then the slope becomes unstable.

Fig. 10 Resisting and driving forces during translational slope failure.

The shear stress developed in the soil by gravitational and other forces (e.g. water flow, seismic activity) impels the slope materials to slide and this tendency is resisted by the soil strength expressed by Mohr-Coulomb theory:

$$S = c + \sigma \tan \varphi, \quad (2)$$

where S is the total shear strength of the soil along the failure plane; σ is the total normal stress; c is the total cohesion of soil; and φ is the total angle of internal friction.

According to Terzaghi (1950), the influence of water on slope stability can be described through the principle of effective stress. Thus, for saturated soils, the Mohr-Coulomb equation is rewritten as:

$$S = c' + \sigma' \tan \varphi', \quad (3)$$

where $\sigma' (= \sigma - u)$ is the effective normal stress at failure when the pore water pressure is u .

In unsaturated or partially saturated soils, water infiltration may lead to a decrease in soil strength associated with a reduction in soil matric suction (Sidle and Bogaard, 2016). Thus, the equation representing the shear strength of unsaturated or partially saturated soils (Eq. 4) requires the inclusion of two additional parameters. The first represents the difference between the pore air pressure and the negative pore water pressure and the second represents the rate of increase of shear strength with the increase in matric suction (Chowdhury et al., 2010):

$$S = c' + (\sigma - u_a) \tan \varphi' + (u_a - u_w) \tan \varphi^b, \quad (4)$$

where $(u_a - u_w) = u_s$ is the matric suction; and φ^b is the angle of internal friction with respect to matric suction. When the soil is saturated, $u_a = 0$ and $u = u_w$.

5.07.5 Concluding Remarks

In nature, one can classify all shallow landslides into two main categories. Rotational slides move along curved surfaces in parent material which is mainly homogeneous and isotropic. Translational slides occur along planar failure surfaces. To a lesser extent, one finds other shallow landslides that show characteristics of the two main types just mentioned. In some cases, the landslide is intermediate between a rotational slide and a translational slide and is called a compound slide. In other cases, the landslide involves two different types of movements occurring in sequence and is called a complex landslide.

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