Patterns of subsidence in landslides

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Abstract The paper spotlights the patterns of ground subsidence in relation to landslides and related phenomena. Three fundamental mechanisms of landslides, namely: head-end interaction, tail-end interaction and the phenomenon of neighbourhood interference, are proposed and illustrated. Implications of coalescence of landslides, and the resulting damage are discussed in terms of the so-called successive, multi-tier and multi-storeyed landslides.

INTRODUCTION

Mountainous landscapes are sculptured by a bewildering variety of landslides, land subsidence and kindred phenomena, taking place over a geological time scale. By carefully mapping the change in slope morphology, especially at intervals of time, it is possible to reconstruct mechanisms causing change. Conversely, if the mechanisms are known, the ensuing changes in slope morphology could be comprehended and explained. Interplay of a multitude of factors — wide in diversity, complex in understanding, and ancient to recent on the time scale, constantly deform, distort, and mould the landslide mass. Study of the genesis, type and character of disturbance within a slope is thus important. The following points deserve consideration:

(a) Study of location-specific case history of development of slopes and slope morphology in the overall context of the macro-geomorphology of the areas. It helps to distinguish between simple ground subsidence and an unfeigned landslide.

(b) Once the existence of a landslide is established, the study of landslide motion at its initiation, development and decay is important. Precursory slope movements, and movement patterns throw light on the mechanism of landslide initiation. Furthermore post landslide motion and the related phases of landslide growth and development modulate slope profiles.

FIELD DATA

Land subsidence without landslides

Evidence of land subsidence alone, no matter how concrete, is not in itself a testimony to the existence of a landslide. Landslides do involve both downward and outward components of movement, although it is not untrue that in some parts, vertical subsidence dominates over the lateral movement, whereas just the opposite may prevail in some other parts.

There are notable cases of pure subsidence, associated, for example, with collapse of underground cavities due to the excessive withdrawal of water, gas and oil from the
ground. Karst topography may be construed from subsurface solution of limestone and
dolomitic rocks, no matter how hard. Such can happen in chalk, gypsum, anhydride and
halite terrains. "Thermokarst" topography generated by thaw of frozen ground may
produce "thaw lakes" and "thaw sinks". In the case of marine erosion, presence of blow
holes may cause roof collapse in the caves formed by the sea. Curious steep wall
depressions, called volcanic sinks, are known to occur in some volcanoes as a
consequence of the outflow of magma.

Subsidence due to leaky underground conduits, or because of water bodies causing
excessive seepage and internal erosion, may also lead to predominantly vertical
subsidence without landslides. A notable example of collapse is an about 100 m wide and
nearly 30 m deep sinkhole at Winter Path, Florida, which occurred in May 1981. The
collapse was partly attributed to drought (Hays, 1981).

Morphology of some first order landslides

By a first order landslide is meant a primary landslide which can be analysed
individually and independently of others subsidence on a slope. Formation of features
like landslide boundary shears, Riedel shears, tension cracks, ground bulge or heave,
land subsidence etc., are common to most landslides. A good deal of information
remains hidden in these features. For example, back-tilting of slipped masses indicates
a rotational mode of failure (Fig. 1(a)). Likewise, formation of a graben usually points
to a compound failure, associated with a non-circular failure surface (Fig. 1(b)). The
study of deformed and broken landslide masses does provide a good idea of the intensity
of the landslide activity.

A graben is one of the spectacular and easily identifiable features of some of the
failed slopes. The mechanism of graben development due to the lateral spread near the

![Fig. 1 Patterns of land subsidence due to some typical first order landslides.](image)
Patterns of subsidence in landslides

free (outer) face of a slope is illustrated by Dobry & Baziar (1992). In the Pelton landslide it formed due to a double wedge failure on a strongly bi-linear slip surface, Cornforth & Vessely (1992). Another example of graben formation is the landslide of February 1953 in the London Clay cliffs near Herne Bay, Kent, southern England (Hutchinson, 1984).

Common landslide situations of practical significance

Some commonly encountered typical landslide situations are illustrated in Fig. 2. It is seen that when a landslide freely advances on a long and continuous sloping terrain, without interference, the landform generated is grossly different from that created when it is obstructed, or provoked. A synthesis of the documented landslide case records yield the following groupings:

- Landslides free to advance uninterruptedly on an expanse of slope continuum (Fig. 2(a)).
- Landslides which suddenly acquire the freedom to fan out and fade away (Fig. 2(b)).
- Landslides subject to toe erosion which provoke landslide motion. At times, rivers get blocked forming landslide dams (Fig. 2(c)).
- Landslides which climb up an opposite slope to come to a halt (Fig. 2(d)).
- Landslides which get obstructed at their lower end (Fig. 2(e)).

Basically all it means is that:

(a) The force fuelling landslide motion, on an open slope, is chiefly contributed by gravity. Occasionally, an additional component of thrust is created when a landslide rapidly receives a charge of debris at its head, perhaps from another landslide on the rear slope, and also when a landslide toe rapidly gets eroded, for example, due to river or sea action.

(b) The energy of a landslide gets dissipated chiefly by the resistance to sliding. Sudden dissipation, however, comes when the slide transits abruptly from a very steep to a flat slope. In doing so, it may fan out; strike against a barrier en route; create a landslide dam; or ride-over the opposite valley bank as the case may be.

The first point mentioned above is vital and provides the fundamental basis to explain landslide motion, later in this paper. The second point is illustrated by some examples below.

Inevitability of landslide equilibrium

All landslides eventually come to rest. In the situations described in Fig. 2, the proof is made. Time of return to equilibrium depends on a number of factors such as slope morphology, characteristics of sliding mass, velocity, volume and area involved. Sometimes dominating obstacles overpower landslides and bring them to a halt.

Landslide dams (Fig. 2(c))

Examples of landslides forming dams in rivers are numerous:
- The Gross Ventre Slide, Wyoming, of 23 June 1925, formed a dam of about 70 m
Fig. 2 Some common landslide situations of practical importance.
height and 2.4 km upstream to downstream. More than 40 million cubic metres of broken limestone, sandstone, siltstone and soil broke away from the side of the steep mountain overlooking the Gross Ventre River (Sowers, 1992).

- Madison Canyon debris flow of 1959 is known to have formed a dam, impounding Hebgen Earthquake Lake. Triggered by a large earthquake (Richter magnitude 7.1), it flowed across the Madison River of western Montana, creating a dam and a lake.
- The Vong Landslide in the eastern Himalaya with a history of repetitive occurrence, blocked the nearly 40 m wide River Teesta for about 20 minutes. Every time the river flushed the debris accumulated at the landslide toe, the reactivation closely followed. Examples of major Himalayan landslide dams are provided by Bhandari (1988).
- Five major landslide dams of the western United States are described by Schuster (1985).

Landslides climbing up the opposite slopes (Fig. 2(d))

A good example of a landslide climbing up the opposite valley wall is the Madison Canyon Landslide in southwestern Montana. Rocks from the mountain top dropped about 400 m and reached the speed of about 160 km h⁻¹, before striking the valley bottom and riding up the opposite valley wall (Schuster et al., 1981).

Fundamental mechanisms instigating landslide motion

The following three fundamental mechanisms of landslide motion are conspicuous because of their dramatic effect on slope morphology:
(a) Head-end interaction: When a landslide gets loaded or intercepted at its head by the lower part of another landslide at the rear (Fig. 3(a)).
(b) Tail-end interaction: When a landslide gets rapidly eroded at its toe by river or sea (Fig. 3(b)) or when it is influenced by another landslide lower below.
(c) Phenomenon of neighbourhood interference: When three or more landslides co-exist as neighbours displaying harmony on the one hand and extreme turbulence on the other.

Head-end and tail-end interactions

The significance of the head-end and the tail-end interactions between a landslide and its external environment are seldom appreciated in full, despite their remarkable capacity to transform landscapes. The first two of the mechanisms chiefly refer to interactions between a landslide and its external environment; the following combinations of the two may occur:
(a) Head-end loading of a landslide without any tail-end erosion.
(b) Tail-end erosion of a landslide without any head-end loading.
(c) Head-end loading as well as tail-end erosion, of a landslide.

Head-end undrained loading of a landslide is known to add to the activating thrust,
and simultaneously bolster pore pressures in the head region of a landslide. The increase in the activating force and the decrease of the resisting force impair the slope stability (Fig. 3(a)).

The tail-end interaction involves removal of landslide tails or tongues by any means, be that due to the river action or due to the tidal action. Loss of the toe support provokes slide (Fig. 3(b)).

The fundamental mechanism of undrained loading of a landslide was suggested by Hutchinson & Bhandari (1972). They demonstrated by field measurements that rapid undrained head loading provides the necessary thrust to trigger motion of low angled mudslides in stiff, fissured clays. The validity of this mechanism has been vindicated by many researchers. For example, Sassa (1984) illustrated the mechanism of initiation of liquefied landslides and debris flows by undrained head loading. Hutchinson et al. (1974) explained potentially dangerous surges in an Antrim mudslide at the Minnis North of northeastern Ireland, using the very same concept.

Combined effect of interactions both at the head-end and the tail-end is illustrated by East Cucaracha slide of 13 October 1986. On the day of the landslide, basalt debris from the rear part of the Gold Hill moved 120 m on to the head of the main body of the East Cucaracha landslide. Nearly 200 000 m$^3$ of the weathered basalt mass surcharged the active slide and provided additional thrust to it. The slide, nearly 240 m deep, extended about 600 m from the canal, covered an area of 10 ha and volume of about 400 000 m$^3$. It nearly closed a navigation canal (Berman, 1991).

**Phenomenon of neighbourhood interference**

By and large, all landslide cases fall into the following two categories:
(a) Neighbouring landslides co-existing without interference or slope violence. Most successive landslides and multiple rotational landslides are the examples.
(b) Neighbouring landslides influencing one another. Multi-storeyed landslides and certain forms of multi-tier landslides are the examples.
Successive slides

Successive slides when pitted against one another may not always interact or interfere much. An example of a triple successive landslide at Gretton Wood is cited by Hutchinson (1967). Similar slides in the Lias clay slopes in an area of the Midlands, England, are reported by Chandler (1970).

Multiple rotational landslides

Multiple rotational failures occur usually when relatively softer materials are capped by stiffer ones. For example, multiple rotational slides at the Folkestone Warren, Kent, on the south coast of England, involved a 45 m thick bed of Gault clay capped by over 120 m of chalk (Hutchinson, 1969). In the absence of a competent cap rock, the rear scarp formed by the initial slip is degraded so rapidly by shallow slips, soil falls and mudflows that unless the erosion at the slide toe is exceptionally severe, the low level of induced stresses fail to bring about a further deep seated failure. Such slides, in cliffs formed entirely of a single geological formation seem rare.

Some other examples are:

- A multi block landslide occurred in the Western Irrigation District on the Bow River in Calgary, Alberta, with the blocks moving at different rates along a common horizontal slip surface, consisting of a thin weak clay seam within the underlying bedrock (Krahan & Wymen, 1984).

- Gorshkov & Yakushova (1977) provide an example of a landslide involving series of blocks which slipped down under their own weight, but whose bedding remained undisturbed, and the surface of the beds got tilted backwards. The damage level was thus low.

Multi-storeyed landslides

By this term, Ter-Stepanian (1977) meant co-existence of several storeys of landslides, stacked one over the other. According to him "Unlike the beads-like landslides, where separate components are situated in the horizontal direction, the multi-storeyed landslides are characterized by a vertical disposition of their components. Another difference is that the components of the bead-like landslides represent the same type of sliding, e.g. earthflows, while the components of the multi-storeyed landslides belong to diverse types of sliding, distinguished by their depth and mechanism. The following groupings are proposed in this paper (Fig. 4).

(a) Landslides in which the boundaries of various tiers do not intersect with each other — the slides may then be called single, double, triple or multi-tiered landslides.

(b) Cases in which the higher tiered landslides are situated within the boundaries of lower tiers, and influence one another and inter slide violence is to be expected — slides may be called single, double or multi-storeyed landslides.

(c) Cases in which boundaries of the various tiers intersect each other in a complex way and may or may not influence one another. The actual ground details should decide the classification.
Each one acts independent of the other, to start with, but may eventually influence one another and grow. (neighbourhood interference Phenomenon)

Overlapping landslide tiers. The second one loads the first and in turn gets loaded by the third. The third one loads both the first and the second. It, therefore, tends to be multi-storeyed.

Basal slip surface of a higher slide tier lies somewhat below the crown of the lower tier, but above its toe. No head loading is seen but removal of lower most tier by sea or river action may provoke slide activity. It looks more like a stepped landslide.

Complex disposition of landslide tiers. The third tier loads the second and the first tier tends to relieve it of lateral support at its toe. Chain of events become crucial to the prediction of landslide motion.

Three successive generations of landslides stacked one above the other fits fully into the description of a multi-storeyed landslide.

Fig. 4 Multi-tier and multi-storeyed landslides (neighbourhood interaction phenomenon).
Multi-storeyed landslides were studied for the first time on the Caucasian coast of the Black Sea in Sochi where a big three-storeyed landslide got developed. The first storey was a rotational landslide 60 m deep, involving blocks of argillites, and sandstones; the second storey was a planar sliding 20 m deep in crushed argillites, and the third storey was an earthflow 6 m deep in products of weathering of the same argillites. A revealing exposition of the concept of multi-tiered landslides is provided by Kyunttsel (1988). He distinguishes between single, double and multi-tiered landslides based on the consideration of first order slides formed and the heights of their respective displacement bases.

CONCLUDING REMARKS

Simple ground subsidence are distinguishable from unfeigned landslides on the basis of the study of slope morphology. Conversely study of slope morphology may provide important clues to the mechanism of slope dynamics. The concepts of head-end interaction, tail-end interaction and to the phenomenon of neighbourhood interaction proposed in this paper are basic. All in depth landslide studies deserve to be tuned to the ground realities, particularly when dealing with landslides other than the first order landslides, such as, for example multi-tier and multi-storeyed landslides.

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REFERENCES
