Landslides
Rainfall Triggered Events and Slope Stability Models

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Abstract
Landslides, while playing an important process in hillslope development, can be extremely destructive to human communities. Engineering models and dynamic models have been used to understand the forces behind landslides. While engineering models focus on internal forces, dynamic models incorporate external and internal processes. Theories of equilibriums and thresholds are also used to form models to understand landslides. Rainfall is often a threshold trigger and several different approaches and theories have been studied are it’s influence on landslides.
Landslides represent a significant role in the development of landforms and hill slope processes. They also represent a significant hazard and problem to human populations in the destruction of settlements and loss of life. It has been estimated, “the total damage in the United States caused by all ground-failure hazards, which include landslides, subsidence, and expansive soils, is greater than the losses from all other natural hazards combined” (Nilsen, 1986, p. 395). In the bay area, costs associated to landslides during the period between “1968 – 1969 was $25 million, $66 million for a single storm in 1982” (Nilsen, 1986, p. 407)

As the human race continues to expand settlement into hill slope areas and modify the landscape, it is important for geomorphologists to understand the processes around landslides and the variable which cause them.

The present literature review will cover how geomorphology approaches landslides, including how landslides are classified and which models are used in the study of them. Furthermore, I will discuss how geomorphology employs the theories of equilibrium and thresholds as a basis for these approaches. Then I will focus on research within threshold triggers and discuss the relationship between rainfall and slope stability.

A significant amount of literature uses the term “landslides” which is not fully accurate, as Olshansky (1990) and Crozier (1986) point out. “Landslide” is often used to describe a variety of slope movements or mass wasting, they can range from a few feet wide or greater than a mile, can occur over a matter of seconds or creep over several years. Olshansky states “mass movements” or “slope movements” are often a more appropriate term than landslide.
While the term landslide is used to describe a wide variety of mass movements, classification of the different types of mass movements has been established with Sharpe’s 1938 work, and more recently with Varnes’s (1975) and Hutchinson’s (1988) work. In this literature review, Varnes’s classifications was most useful because it focused on landslides such as falls, slides, flows, and complex types (and excluded creep and frozen ground phenomena).

Varnes describes and classifies the different types of movement relative to each other, this is because often landslides are not clearly in one category or classification but hold characteristics of several. For example, ‘slide’ refers to the “relative motion between stable ground and moving ground in which the vectors of relative motion are parallel to the surface of separation or rupture” (Varnes, 1975, p. 11). However, Varnes describes flow in comparison as the “distribution and continuity of relative movements of particles within the moving mass itself” (Varnes, 1975, p.11). Thus, there are several types of classification of landslides, falls, slides, topples, lateral spreads, flows, and complex. However, research is often focused more on the forces within and those acting upon (undercutting) than on what type of classification the movement is.

The main forces acting within a hillslope are internal forces, such as gravity, and external forces, such as rainfall. When the two are applied, a state of stress is present. There are many ways stress can be expressed, but if often produces strain. Strain in turn, causes deformation and is “measured as a ratio of the change in dimensions of the stressed body to its original dimensions” (Zaruba, 1982, p. 103). How much strain that is needed to deform a rock depends on the strength of the rock. Below is a diagram which illustrates the basic forces working within a hillslope.
Static and Dynamic Models of Hillslope Stability

How these forces are measured and what variables to apply them to vary in the different models and approaches used in both geomorphology and engineering.

Engineering models tend to focus on landslide mitigation and control and often look at landslides in their stable state and what stimuli caused them to become destabilized. They look at the forces that caused the slip, and measure the internal forces by putting values on them and in putting them into an equation. The strength of the soil is then calculated and the two are put into a ratio – known as a factor of safety. Generally, it is a ratio of –

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\text{Factor of Safety} = \frac{\text{Sum of resisting forces}}{\text{Sum of driving forces}}
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Therefore, a slope with a factor of safety of 1 or more would be considered stable, less than 1 would be an unstable slope.

Another static model developed was that by Peterson (1955) called the “method of slices” where he applied this technique to “a slip surface which was circular ace in cross-section” (Dikau, et. al, 1996, p. 232).
In using this technique, the model was able to subdivide the slide mass into sections which allowed an easier way to measure the internal stress within the hill slope. Since the development of computers and greater availability of processing power, the models have become more complex and have been able to incorporate more variables, and is still used as a basis for many static models today. Static models contributed significantly to understanding how concepts such as effective stress, the role of pore pressure and the factors that control pore pressure, as well as the dependence on the strain and strength of soils, peak strengths and residual strengths effect hill slope stability. (Dikau et. Al., 1996)

However, geomorphologists and other geosciences use dynamic models when looking at landslides. Dynamic models look at the movement of landslides once they have become destabilized, and are based on the equation of motion, “when the factor of safety goes below 1, the ratio of resistance to driving force then becomes less important then the difference between them” (Selby, 1993, p.268)
Further, dynamic models look beyond the geo-mechanical conditions that exist at the time of the failure to the history and slope of its environment. These types of models can include: tectonic uplift, fluvial downcutting, weathering related changes in material properties, depth of regolith, climate change, vegetation change, and previous geomorphic activity. In general, dynamic models emphasize the processes in the development of a state of stability where a landslide can be triggered by existing factors. These models can encompass varying scales and measurements of time and space. (Crozier, 1986)

Crozier calls the geomorphic processes that result from the influence of climate on vegetation, soils, topography – “alternating exogenic regimes” (1999, p. 151). He acknowledges that landforms formed by climatic conditions may take a long time, and other processes may also be involved in the development and change of the hillslope, that is why he applied “alternating” to the name.

**Equilibriums and Thresholds**

The theory of thresholds in landslides is discussed because the question is asked – why do some rainstorms produce landslides while others do not? (Crozier, 1986). A threshold is loosely defined as “a balance between opposing tendencies – a boundary between separate system states” (Bull, 1991, p. 10). Thresholds are an important factor when studying landslides because it acknowledges that non-linear forces are at work especially with the involvement of fluvial forces. The theory of thresholds evolved out of the concept of magnitude and frequency, specifically, how the importance of an event is governed by the magnitude of the energy it releases on the landscape and the frequency
with which it recurs. Also looked at is the work performed by processes going on in between major events. (Bull, 1991; Selby, 1993; Dikau et al., 1996)

When a landslide occurs, a threshold has been passed, which means the strength of a rock or soil material exceeded an applied stress. Selby describes three types of ways a threshold can be passed, a reduction in internal resistance by weathering of soil which lowers the shear stress, a gradual change in landform, and finally an increase in external stress, such as rainfall. (Selby, 1993)

Crozier discusses four different methods for identifying thresholds in hillslopes; theoretical models, which measure precipitation and often determine a factor of safety, empirical tests, where field experiments are used and landslide are purposefully induced. The third and fourth methods are when there is a spatial or temporal correlation of landslide occurrence and climate events.

The strength-equilibrium of a rock slope is when there is a balance between the inclination of the hillslope and the resistance to failure of the rock mass. The figure to the left plots out that “all rock slope units which have gradients in conformity with the rock-mass strength, the plotted data points fall within the strength-equilibrium envelope” (Selby, 1993, p. 368). However, this is only representative for slopes which have not been undercut, and have not been subject to any human change.
Rainfall Triggered Thresholds

Rainfall influence slope stability indirectly through its effect on pore pressure, and thresholds passed due to rainfall have been termed “critical rainfall” or “triggering influence”. Caine hypothesized around the way rainfall triggered for large catastrophic landslides and focused on debris type flows. His main hypothesis was that failures are not caused by the total depth of rainfall or by the intensity of the rainfall but through a combination of both. In his methods he focused on undisturbed slopes where debris flows had occurred and rainfall intensities and durations had been measured. While acknowledging the data had inaccuracies, he found it showed a general threshold for critical rainfall. He expressed it in the following equation -- \( I = 14.82 \ D^{-0.39} \), where \( I \) is the rainfall intensity and \( D \) is the duration. He showed there was a threshold which could be calculated between a range of 10 minutes and 10 days depending on the intensity and duration of rainfall.

Caine’s research is logical, and the data supports his hypothesis. However, it reflected a small portion of mechanics and processes involved in landslides and slope stability by only focusing on catastrophic landslides on undisturbed slopes. Furthermore, he did not address many of the other characteristics which are influenced by rainfall, such as vegetation, regolith, or antecedent water content.
Another study which focused on the probability of landslides during rainfall events was carried out by Finlay, Fell, and Maguire in Hong Kong Island in 1997. This research was similar to Caine’s in that they attempted to establish thresholds, except their study area only encompassed human modified slopes. They carried out a spatial statistical analysis and tried to predict landslides during a 1 to 100 year rainfall event. For data, they used rainfall data collected throughout Hong Kong Island, and for landslides they included landslides that had been reported to the government.

After analysis, they were able to show a threshold for rainfall triggered landslides can be expected and hypothesized around the relationship between the two variables. Out of this they were able to develop the “average probability of a landslide when given a rain event” (Finaly et al., 1997, p. 824).

However, the authors did acknowledge that a significant portion of their data was missing from the rain gauges and so they had to extrapolate out for the missing data. Also, similar to Craine’s research, they did not incorporate additional characteristics, only
rain of the day of the landslide event. Furthermore, the authors concluded antecedent water did not have a significant influence on threshold levels, which seemed contradictory to other research, such as that by Crozier.

Crozier’s research also focused on urban areas and attempted to develop a threshold for rainfall triggered landsides. His research was superior in my opinion to the Hong Kong Island work in that it incorporated additional elements influencing thresholds.

Crozier developed an Antecedent Water Status Model (AWSM) which calculated an index of soil water, which incorporated soil water (antecedent water) and event water. Specifically, the index was based on:

- Deficit storage on day 0
- Deficit storage for the day before
- Precipitation on day 0
- Potential evapotranspiration for day 0

He measured daily rainfall and how the amount of water in the soil measured as compared to the index. If rainfall measured high on the index, then the chance of the threshold being triggered was greater, and a landslide was more likely.

In his results, Crozier’s index was only partially accurate, 38%, at predicting significant landsides. However, the model was able to conclude there were certain maximum and minimum threshold limits which could be established, but also acknowledged there was a significant amount in between the thresholds.

I thought Crozier’s model was better than Caine’s or Fell et. al. because it took into account antecedent water levels as well as drainage. By doing this, the research
incorporated the local and historical context of each slope and potential slide. Crozier discussed the importance of the local and historical context is landslide assessment in his 1986 book *Landslides: Causes, Consequences & Environment*. He sited several case studies in which the local and historical context were used to explain how it affected each landslide.

Another example of research looking at a local and historical context was in Olshansky’s 1990 work. Similar to Crozier, he discussed case studies of landslides, and started his research with looking at the setting of the landslide, which included location, topography, geology, and if there was development on the slope. Then he looked at the landslide event, and the mechanisms that caused it. This included looking at how the landslide occurred, what were the geomorphic conditions and scale, and finally what triggered the landslide. When looking at mechanisms or the geomorphic process, he focused on water, as he felt it is the main triggering mechanism for landslides.

Again, similar to Crozier, he acknowledged that both seasonal and antecedent rainfall and intensities of rainfall were often the cause of triggering a threshold, and models could be put together to conceptualize the process. However, he also concluded that while the models can measure maximum and minimum thresholds, and could therefore capture the probability of frequency of landslide events, the models could not be site-specific.

The theories around antecedent water and event rainfall have been used for real-time monitoring of landslides, and are currently in use at five sites throughout the US. The objective is to not predict landslides, but to sense when the landslide has occurred and send emergency personnel to mitigate as much of the damage as possible. The real-
time monitoring system was developed by the USGS, and involves a remote system which monitors ground movement and ground water pressure every second. The amount of movement is recorded by extensometers that detect stretching or shortening, and ground water within the slope is also measured.

In conclusion, landslides are an important process in hillslope development and can be an extremely destructive force for human communities. It is important for researcher in geomorphology to continue to try to understand the processes and forces at work in landslides.

Bibliography


New York, NY.