Earth and Planetary Science Letters 287 (2009) 31–42

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

journal homepage: www.elsevier.com/locate/epsl

Size distributions and failure initiation of submarine and subaerial landslides

U.S. ten Brink [a,*], R. Barkan [b], B.D. Andrews [a], J.D. Chaytor [a]

[a] U.S. Geological Survey, Woods Hole Science Center, Woods Hole, MA 02543, USA
[b] Dept. of Geophysics and Planetary Sciences, Tel Aviv University, Tel Aviv, 69978, Israel

ARTICLE INFO

Article history:
Received 19 March 2009
Received in revised form 22 July 2009
Accepted 24 July 2009
Available online 17 September 2009

Editor: R.D. van der Hilst

Keywords:
Inverse Power Law
Lognormal distribution
Continental slope
U.S. East Coast
Ground shaking
Landslides
Slope stability
Northridge earthquake
Self-organized criticality

ABSTRACT

Landslides are often viewed together with other natural hazards, such as earthquakes and fires, as phenomena whose size distribution obeys an inverse power law. Inverse power law distributions are the result of additive avalanche processes, in which the final size cannot be predicted at the onset of the disturbance. Volume and area distributions of submarine landslides along the U.S. Atlantic continental slope follow a lognormal distribution and not an inverse power law. Using Monte Carlo simulations, we generated area distributions of submarine landslides that show a characteristic size and with few smaller and larger areas, which can be described well by a lognormal distribution. To generate these distributions we assumed that the area of slope failure depends on earthquake magnitude, i.e., that failure occurs simultaneously over the area affected by horizontal ground shaking, and does not cascade from nucleating points. Furthermore, the downslope movement of displaced sediments does not entrain significant amounts of additional material. Our simulations fit well the area distribution of landslide sources along the Atlantic continental margin, if we assume that the slope has been subjected to earthquakes of magnitude ≤6.3. Regions of submarine landslides, whose area distributions obey inverse power laws, may be controlled by different generation mechanisms, such as the gradual development of fractures in the headwalls of cliffs. The observation of a large number of small subaerial landslides being triggered by a single earthquake is also compatible with the hypothesis that failure occurs simultaneously in many locations within the area affected by ground shaking. Unlike submarine landslides, which are found on large uniformly-dipping slopes, a single large landslide scarp cannot form on land because of the heterogeneous morphology and short slope distances of tectonically-active subaerial regions. However, for a given earthquake magnitude, the total area affected by subaerial landslides is comparable to that calculated by slope stability analysis for submarine landslides. The area distribution of subaerial landslides from a single event may be determined by the size distribution of the morphology of the affected area, not by the initiation process.

1. Introduction

Submarine slope failures are a major sediment-transport process from the continental shelf and upper slope to the deep ocean (e.g., Hutton and Syvitski, 2004). Slope failure can take different forms such as translational or rotational slides, sediment spreads, debris avalanches, debris flows, and mud flows (Locat, 2001; Locat and Lee, 2002). The different failure forms likely represent the different geotechnical and rheological properties of the failed material, and possible layering and heterogeneity of the site (Locat and Lee, 2002). For example, Harbitz (1992) suggested that a significant part of the Storegga slide failed as a spread. Locat et al. (2009) suggested that the Currituck failure was a retrogressive failure of two separate slides, the deeper one failing first, which caused the adjacent shallower one to fail. As with other retrogressive failures, it is unclear whether these two failures occurred during the same event or were separated in time. The temporal development of slope failure is fundamental to understanding the landslide process, and is also important to the assessment of landslide-generated tsunami, whose runup depends to a large extent on the size of the landslide (e.g., Geist et al., 2009).

In the absence of direct observations, scientists have made assumptions about failure dynamics. The most common assumption is that a landslide process is a cascade or an avalanche process (e.g., Densmore et al., 1998; Guzzetti et al., 2002; Malamud and Turcotte, 2006), known as self-organized criticality (Bak et al., 1988; Hergarten, 2003). This process assumes that failure nucleates in one or more locations, spreads to surrounding regions, and can coalesce to generate large failures. This process is often simulated by cellular-automata models (e.g., Malamud and Turcotte, 2006). The area–frequency distribution of this process is an inverse power law (e.g., Guzzetti et al., 2002).

The avalanche model is by its nature an additive process whose duration can vary widely and cannot be determined at the start of the

---

[*] Corresponding author.
E-mail address: utenbrink@usgs.gov (U.S. ten Brink).

0012-821X/$ – see front matter © 2009 Elsevier B.V. All rights reserved.
doi:10.1016/j.epsl.2009.07.031

process (e.g., Turcotte and Malamud, 2004). The most famous example of an additive process in the Earth Sciences is the frequency–magnitude relationship of earthquakes (Gutenberg and Richter, 1944):

$$\log N = a - bM \quad (1)$$

where N is the number of earthquakes with magnitude greater than M occurring over a given time, and a and b are constants. This distribution implies that earthquakes grow from nucleation points and their final magnitude cannot be predicted (e.g., page 274 in Stein and Wysession (2003)). The deviation from power law relationship for small earthquakes is often explained by an incomplete catalog for very small earthquakes, and the deviation at the largest magnitudes is explained by the physical limitation of fault size in different regions (e.g., page 275 in Stein and Wysession (2003)).

An inverse power law distribution was also invoked for different physical aspects of subaerial (Dai and Lee, 2001; Guzzetti et al., 2002; Dussauge et al., 2003; Guthrie et al., 2008; Malamud et al., 2004; Sugai et al., 1994) and submarine (ten Brink et al., 2006a; Micallef et al., 2008) landslides. In the majority of these publications, however, the inverse power law distribution applies only to a truncated portion of the dataset (Stark and Hovius, 2001). To fit the entire range of landslide areas, Malamud et al. (2004) proposed a three-parameter inverse Gamma distribution and Stark and Hovius (2001) proposed a double Pareto function. The misfit of an inverse power law distribution to the portion covering the smallest sizes was attributed to undersampling (e.g., Burroughs and Tebbens, 2001; ten Brink et al., 2006a), to an artifact of the mapping resolution (Stark and Hovius, 2001), or to the transition from a friction-controlled resistance to a cohesion-controlled resistance (Guzzetti et al., 2002).

A few landslide datasets, however, have distributions that are not easily approximated by an inverse power law distribution. Issler et al. (2005) obtained a logarithmic distribution for the volume of depositional lobes from the Storegga slide. Lognormal distributions were found for the areas of landslides in Kashmir (Dunning et al., 2007), and for volumes of deposits of pre-historic turbidity currents in Italy (Talling et al., 2007). Most recently, Chaytor et al. (2009) obtained an excellent lognormal fit to the size distribution of the areas and volumes of 106 submarine slope failure along the Atlantic continental slope ($R^2 = 0.9938$; Figs. 1 and 2). Chaytor et al. (2009) attempted to explain this observation by assuming that the actual size distribution of Atlantic slope failures follows an inverse power law distribution, but that distribution was modified by the conditional probability of preferentially identifying landslides of certain sizes in the bathymetry data to give the appearance of a lognormal distribution.

The portion of the Atlantic continental slope and rise, analyzed here, is a vast area (400,000 km^2), which, with the exception of a 10–20 km-wide upper slope has seafloor slopes $<2°$ (Fig. 1A). Many of the landslides, especially, open slope landslides, initiate on these low-angle slopes (Twichell et al., 2009). The slope of the continental margin could further be characterized as monotonic, i.e., the direction of greatest slope is oriented in the same general direction (seaward) over a large area (Fig. 1B).

In this paper, we show that a simple earthquake-triggered landslide mechanism can produce area distributions that can often be approximated by a lognormal distribution. Although an inverse power law can sometimes approximate the tails of these distributions, we question the physical significance of an inverse power law distribution for landslides. Specifically, we question the assumption that during an event the failure always grows from single or several point-failures and that its final size is unpredictable. (We cannot discard circumstances where the final landslide size may be unpredictable and we briefly discuss one such mechanism at the end of section 4.) The failed material may coalesce into debris flows and turbidity flows as it moves downslope (e.g., Tripsanas et al., 2008), but the downslope movement itself does not excavate significant amounts of new material. Although it is difficult to assess the general validity of this hypothesis, at least one historical record suggests that it could be correct in some cases. Multibeam bathymetry and side-scan sonar surveys of the 1929 Grand Banks landslide, which was triggered by a M7.2 ± 0.3 earthquake, did not reveal evidence for a single major headwall scarp or for a massive slump region (Piper et al., 1999; Mosher and Piper, 2007). Two thirds of the total failure area was characterized by patchy failures with intervening areas showing no evidence of failure. Had the failure been a downslope or upslope cascading process from one or several nucleation points, it is likely that the entire area would have shown evidence for seafloor failure.

The seismological record is also compatible with the hypothesis that failure occurs simultaneously in the area affected by shaking. If landslides nucleate in one location and then propagate along the failure plane similar to earthquake propagation, we would expect large double-couple landslide earthquakes to occur when a large submarine slope failure takes place. Such earthquakes were not detected during the 1929 Grand Banks (Bent, 1995) and the 1998 Papua New Guinea tsunamigenic landslides (Okal and Synolakis, 2001). That said, single-force earthquakes do occur sometime during landslide events (Kanamori and Given, 1982; Okal, 2003). However, these earthquakes are characterized by predominantly long-period surface waves, which are excited by the accelerating and decelerating sliding mass as it interacts with the earth surface during the runout of the debris avalanche (Kanamori and Given, 1982).

We focus here on earthquake-induced landslides from submarine slope failures, and do not discuss other triggering mechanisms (e.g., salt movement, gas hydrate dissociation; Hampton et al., 1996), because triggering of landslides by gas hydrate dissociation has been recently questioned (Hornbach et al., 2007; Twichell et al., 2009), and salt movement is limited to specific locations. Furthermore, examining the statistical characteristics of submarine landslides along the U.S. Atlantic margin, Booth and O'Leary (1991) commented that “the occurrence of large-scale mass movements on gentle slopes implies that regional rather than local factors have been dominant”. They further noticed that mass movements along the Atlantic margin tend to be disintegrative and that slope angle does not seem to be an important factor controlling the initiation of a mass movement. These observations suggested to them that a relatively rapid stress increase or strength reduction took place within the sediment column, most likely because of transient earthquake loading (Booth and O'Leary, 1991).

The second part of the paper examines the viability of our hypothesis in the subaerial environment. We suggest that similar to submarine landslides, subaerial landslides also initiate by simultaneous failure over a large area and do not develop as a cascading process. However, the size distribution of these landslides is limited by the morphological characteristics of the failure region.

2. Simulations of earthquake-induced landslides

To test the viability of the hypothesis, we generated Monte Carlo simulations of earthquakes and their expected failure areas and compared their area distribution with the observed distribution along the U.S. Atlantic continental margin (Fig. 2). The maximum expected failure area was estimated using a slope stability analysis with undrained strength properties, following the method and parameters outlined in ten Brink et al. (2009). The method is reviewed here briefly.

Slope failure of sediments is assumed to initiate when the pseudo-static stress, which includes the downslope gravitational stress plus horizontal earthquake loading, exceeds the undrained shear strength. The vertical ground-motion component contains relatively little of the total energy of shaking and is therefore ignored in strong-motion studies (e.g., Harp and Wilson, 1995). This critical pseudo-static stress