Coseismic Landslide Patterns in Three Subduction Earthquakes: Field Observations and Cascadia Implications

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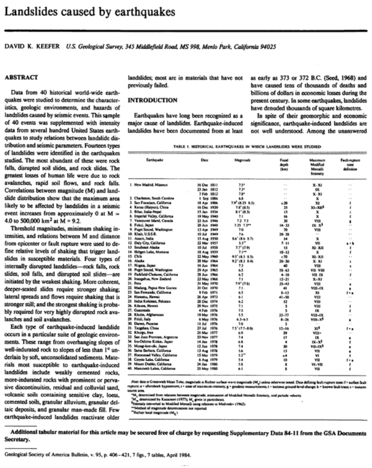
Background

Keefer 1984



Landslides caused by earthquakes

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ABSTRACT

Data from 40 historical world-wide earthquakes were studied to determine the characteristics, geologic environments, and hazards of landslides caused by seismic events. This sample of 40 events was supplemented with intensity data from several hundred United States earthquakes to study relations between landslide distribution and seismic parameters. Fourteen types of landslides were identified in the earthquakes studied. The most abundant of these were rock falls, disrupted soil slides, and rock slides. The greatest losses of human life were due to rock avalanches, rapid soil flows, and rock falls. Correlations between magnitude (M) and landslide distribution show that the maximum area likely to be affected by landslides in a seismic event increases from approximately 0 at M = 4.0 to 500,000 km² at M = 9.2.

Threshold magnitudes, minimum shaking intensities, and relations between M and distance from epicenter or fault rupture were used to define relative levels of shaking that trigger landslides in susceptible materials. Four types of internally disrupted landslides—rock falls, rock slides, soil falls, and disrupted soil slides—are initiated by the weakest shaking. More coherent, deeper-seated slides require stronger shaking; lateral spreads and flows require shaking that is stronger still; and the strongest shaking is probably required for very highly disrupted rock avalanches and soil avalanches.

Each type of earthquake-induced landslide occurs in a particular suite of geologic environments. These range from overhanging slopes of well-indurated rock to slopes of less than 1° underlain by soft, unconsolidated sediments. Materials most susceptible to earthquake-induced landslides include weakly cemented rocks, more-indurated rocks with prominent or pervasive discontinuities, residual and colluvial sand, volcanic soils containing sensitive clay, loess, cemented soils, granular alluvium, granular deltaic deposits, and granular man-made fill. Few earthquake-induced landslides reactivate older landslides; most are in materials that have not previously failed.

INTRODUCTION

Earthquakes have long been recognized as a major cause of landslides. Earthquake-induced landslides have been documented from at least as early as 373 or 372 B.C. (Seed, 1968) and have caused tens of thousands of deaths and billions of dollars in economic losses during the present century. In some earthquakes, landslides have denuded thousands of square kilometres.

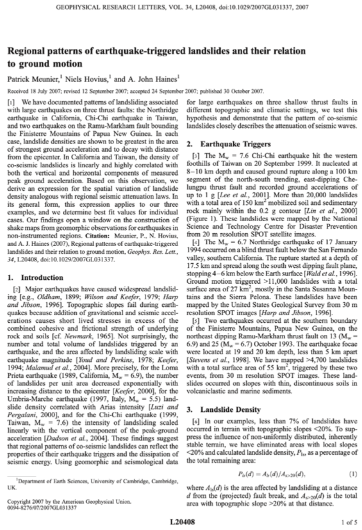
In spite of their geomorphic and economic significance, earthquake-induced landslides are not well understood. Among the unanswered

TABLE 1. HISTORICAL EARTHQUAKES IN WHICH LANDSLIDES WERE STUDIED

Additional tabular material for this article may be secured free of charge by requesting Supplementary Data 84-11 from the GSA Documents Secretary.

Geological Society of America Bulletin, v. 95, p. 406–421, 7 figs., 7 tables, April 1984.

Meunier et al. 2007



GEOPHYSICAL RESEARCH LETTERS, VOL. 34, L20408, doi:10.1029/2007GL031337, 2007

Regional patterns of earthquake-triggered landslides and their relation to ground motion

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[1] We have documented patterns of landsliding associated with large earthquakes on three thrust faults: the Northridge earthquake in California, Chi-Chi earthquake in Taiwan, and two earthquakes on the Ramu-Markham fault bounding the Finisterre Mountains of Papua New Guinea. In each case, landslide densities are shown to be greatest in the area of strongest ground acceleration and to decay with distance from the epicenter. In California and Taiwan, the density of co-seismic landslides is linearly and highly correlated with both the vertical and horizontal components of measured peak ground acceleration. Based on this observation, we derive an expression for the spatial variation of landslide density analogous with regional seismic attenuation laws. In its general form, this expression applies to our three examples, and we determine best fit values for individual cases. Our findings open a window on the construction of shake maps from geomorphic observations for earthquakes in non-instrumented regions. **Citation:** Meunier, P., N. Hovius, and A. J. Haines (2007), Regional patterns of earthquake-triggered landslides and their relation to ground motion, *Geophys. Res. Lett.*, *34*, L20408, doi:10.1029/2007GL031337.

1. Introduction

[2] Major earthquakes have caused widespread landsliding [e.g., *Oldham*, 1899; *Wilson and Keefer*, 1979; *Harp and Jibson*, 1996]. Topographic slopes fail during earthquakes because addition of gravitational and seismic accelerations causes short lived stresses in excess of the combined cohesive and frictional strength of underlying rock and soils [cf. *Newmark*, 1965]. Not surprisingly, the number and total volume of landslides triggered by an earthquake, and the area affected by landsliding scale with earthquake magnitude [*Youd and Perkins*, 1978; *Keefer*, 1994; *Malamud et al.*, 2004]. More precisely, for the Loma Prieta earthquake (1989, California, M_w = 6.9), the number of landslides per unit area decreased exponentially with increasing distance to the epicenter [*Keefer*, 2000], for the Umbria-Marche earthquake (1997, Italy, M_w = 5.5) landslide density correlated with Arias intensity [*Luzi and Pergalani*, 2000], and for the Chi-Chi earthquake (1999, Taiwan, M_w = 7.6) the intensity of landsliding scaled linearly with the vertical component of the peak-ground acceleration [*Dadson et al.*, 2004]. These findings suggest that regional patterns of co-seismic landslides can reflect the properties of their earthquake triggers and the dissipation of seismic energy. Using geomorphic and seismological data for large earthquakes on three shallow thrust faults in different topographic and climatic settings, we test this hypothesis and demonstrate that the pattern of co-seismic landslides closely describes the attenuation of seismic waves.

2. Earthquake Triggers

[3] The M_w = 7.6 Chi-Chi earthquake hit the western foothills of Taiwan on 20 September 1999. It nucleated at 8–10 km depth and caused ground rupture along a 100 km segment of the north-south trending, east-dipping Chelungpu thrust fault and recorded ground accelerations of up to 1 g [*Lee et al.*, 2001]. More than 20,000 landslides with a total area of 150 km² mobilized soil and sedimentary rock mainly within the 0.2 g contour [*Lin et al.*, 2000] (Figure 1). These landslides were mapped by the National Science and Technology Centre for Disaster Prevention from 20 m resolution SPOT satellite images.

[4] The M_w = 6.7 Northridge earthquake of 17 January 1994 occurred on a blind thrust fault below the San Fernando valley, southern California. The rupture started at a depth of 17.5 km and spread along the south west dipping fault plane, stopping 4–6 km below the Earth surface [*Wald et al.*, 1996]. Ground motion triggered >11,000 landslides with a total surface area of 27 km², mostly in the Santa Susanna Mountains and the Sierra Pelona. These landslides have been mapped by the United States Geological Survey from 30 m resolution SPOT images [*Harp and Jibson*, 1996].

[5] Two earthquakes occurred at the southern boundary of the Finisterre Mountains, Papua New Guinea, on the northeast dipping Ramu-Markham thrust fault on 13 (M_w = 6.9) and 25 (M_w = 6.7) October 1993. The earthquake focae were located at 19 and 20 km depth, less than 5 km apart [*Stevens et al.*, 1998]. We have mapped >4,700 landslides with a total surface area of 55 km², triggered by these two events, from 30 m resolution SPOT images. These landslides occurred on slopes with thin, discontinuous soils in volcaniclastic and marine sediments.

3. Landslide Density

[6] In our examples, less than 7% of landslides have occurred in terrain with topographic slopes <20%. To suppress the influence of non-uniformly distributed, inherently stable terrain, we have eliminated areas with local slopes <20% and calculated landslide density, P_{ls}, as a percentage of the total remaining area:

$$P_{ls}(d) = A_{ls}(d)/A_{s>20}(d), \quad (1)$$

where $A_{ls}(d)$ is the area affected by landsliding at a distance d from the (projected) fault break, and $A_{s>20}(d)$ is the total area with topographic slope >20% at that distance.

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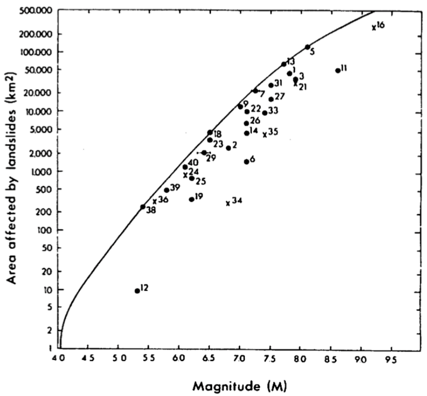

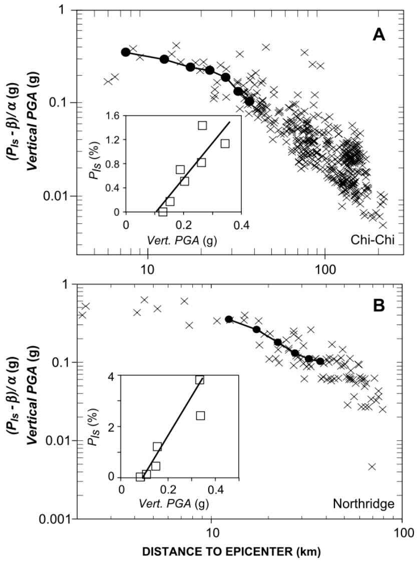

2001 M8.4 Southern Peru Earthquake

3 Ground Failure

INTRODUCTION

Ground failure occurred throughout the much of the region shaken by 23 June 2001 Southern Peru earthquake. Although few, if any, casualties were directly attributable to ground failure, damage caused by ground failure was costly and pervasive. Because ground failure had a marked effect on the transportation infrastructure of the region, it had a significant impact on earthquake rescue and recovery efforts. Highway damage and bridge closures in the days and weeks that followed the event greatly hindered response efforts.

This chapter reports on observed ground failures and includes information collected by the geotechnical and landslide reconnaissance teams that visited the region shortly after the earthquake occurred. The National Science Foundation (NSF)-sponsored team and the U.S.-Peruvian geotechnical reconnaissance team collected the majority of the information presented in this chapter. A second joint U.S.-Peruvian reconnaissance team, led by the U.S. Geologic Survey (USGS), also contributed additional landslide data.

Reconnaissances was performed in a thorough and efficient manner due to the perishable nature of geotechnical field data, which can be altered or destroyed by cleanup activities and/or climatic events. The geotechnical teams adopted a reconnaissance philosophy consistent with that of teams studying pervious earthquakes (e.g., Bardet et al. 2000; Stewart et al. 2001); that is, to collect as much high quality field data as possible in the time available. Interpretation of the data was not made in the field; rather this task will be completed only after comprehensive analyses of the collected data. Accordingly, this article does not present conclusive interpretations of the field data.

The observations reported here are unique, primarily because of the large magnitude of the earthquake (M_w = 8.4; HRV) and the widespread area over which ground failure occurred. For the purpose of this article, ground failure refers to all types of earthquake-induced coseismic permanent ground deformations, including those resulting from soil liquefaction, landslides, and seismic compression (i.e., cyclic densification of unsaturated soil). The teams also reviewed the performance of earth-retaining structures.

GEOTECHNICAL RECONNAISSANCE TEAMS

The National Science Foundation (NSF) sponsored the geotechnical reconnaissance team. The team observed and compiled data on landslides, liquefaction, seismic compression, site and apparent topographic effects, and mine performance. The latter two topics are discussed in Chapter 2, Ground Motion and Site Response and in Chapter 4, Mines—Geotechnical Aspects.

The NSF-sponsored reconnaissance was performed in two stages: aerial reconnaissance followed by reconnaissance by vehicle. Low-altitude aerial reconnaissance was flown in a chartered fixed-wing aircraft over the earthquake-affected region where local officials had reported damage. Damage observations and information collected during the aerial reconnaissance was later used to plan and optimize the vehicle-based reconnaissance.

Wartman et al. 2003

"The types of landslides and types of materials that produced landslides in this earthquake are similar to those of the vast majority of other earthquakes worldwide (Keefer 1984). However, two observations stand out as differing from the general pattern observed in other earthquakes:

- "First, the lack of large landslides throughout most of the region ... is unusual for an earthquake of this magnitude that affects a region where steep slopes are so prevalent."
- "Second, the widespread collapse of quebrada banks in the area ... is unusual in its severity."
- *Why? Extremely dry conditions, and Anomalously low seismic shaking*

2007 M8 Pisco Peru Earthquake

ASPECTOS GEOTÉCNICOS DEL SISMO DE PISCO, PERÚ DEL 15 DE AGOSTO DEL 2007[1]

Adrián Rodríguez-Marek[2], Jorge E. Alva Hurtado[3], Brady Cox[4], Jorge Meneses[5], Gonzalo A. Montalva[6], Viviana Moreno[7], Manuel Olcese[7], Rodolfo Sancio[8], Joseph Wartman[9]

Resumen: Este artículo presenta un resumen de las observaciones realizadas durante un reconocimiento de los efectos geotécnicos del sismo de Pisco ocurrido el 15 de agosto del 2007 en la zona central de la costa del Perú. Este sismo de magnitud (M_w) 8.0 causó daños importantes a obras de ingeniería civil en una amplia zona que incluye las ciudades de Ica, Pisco, Cañete y Chincha. Desde una perspectiva geotécnica, los aspectos más relevantes de este sismo son la gran extensión de licuación de suelo observada en la zona mesosísmica y el considerable daño que causó en las zonas urbanas y en la infraestructura de transporte. En particular se destaca la documentación de un deslizamiento lateral que involucró un área de al menos 3 km^2 de terreno y asentamientos de hasta 0.9 m observados en estructuras livianas. El sismo también causó varios deslizamientos de talud que resultaron en bloqueos de carreteras. También se presenta un análisis preliminar de los registros de aceleraciones obtenidos durante el sismo.

Palabras clave: desplazamiento lateral, movimientos del terreno, licuación, observaciones en terremotos, sismo de Pisco.

GEOTECHNICAL ASPECTS OF THE AUGUST 15, 2007 PISCO, PERU EARTHQUAKE

Abstract: This paper summarizes geotechnical observations of the August 15, 2007 Pisco earthquake that took place in the central coast of Peru. This M_w 8.0 earthquake caused significant damages to civil infrastructure in a wide area that included the cities of Ica, Pisco, Cañete, and Chincha. From a geotechnical perspective, the most important aspects of this earthquake are the large extent of observed soil liquefaction in the mesoseismic area, and the significant damage liquefaction caused to urban areas and the transportation infrastructure. Two particular case histories include a lateral spread that involved an area of 3 km^2 and liquefaction-induced settlements up to 0.9 m in lightweight structures. The earthquake also caused various landslides that resulted in road closures. A preliminary analysis of the strong motion records obtained during the earthquake mainshock is also presented.

Keywords: earthquake observations, lateral spread, liquefaction, Pisco earthquake, strong ground motion.

INTRODUCCIÓN

El miércoles 15 de agosto de 2007, a las 6:40 PM hora local, un sismo de magnitud 8.0 en la escala de momento sacudió la región costera de Perú central. El sismo ha sido referido como el sismo de Pisco o el de Ica (Pisco fue la ciudad más afectada, e Ica es el departamento donde las ciudades de Pisco e Ica están localizadas). En este artículo se usará la denominación "sismo de Pisco". El sismo causó daños severos a las ciudades de Pisco, Ica, Cañete y Chincha, y se sintió fuertemente en Lima, la ciudad capital de Perú. En respuesta a este evento, la organización de Ingeniería

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Journal paper highlights extremely large, lateral spreads and poor performance of cut slopes along roads.

- Three landslide settings

1. **Paracas Peninsula**: young marine sedimentary rocks, massive coastal losses
2. **Coastal Plains**: dominant ground failures were liquefaction and lateral spreading
3. **Andes Mountains**: Range of landslide types

- Significant large failures along the coast and comparatively few failures inland

- Inverse relationship found between PGA and landslide intensity in parts of the Andes Mountains

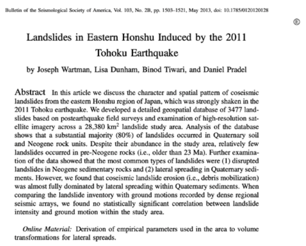
- Role of subduction ground motion

- Local levels of high-intensity shaking cause coastal failures in soft marine rocks. (Paracas)

- Long durations promote coalescence of failures into large mass movements, especially in areas where landslide failures can grow unconstrained. (Coastal Plains)

- Relatively modest inland PGAs. (Andes)

2011 M9.1 Tohoku Earthquake



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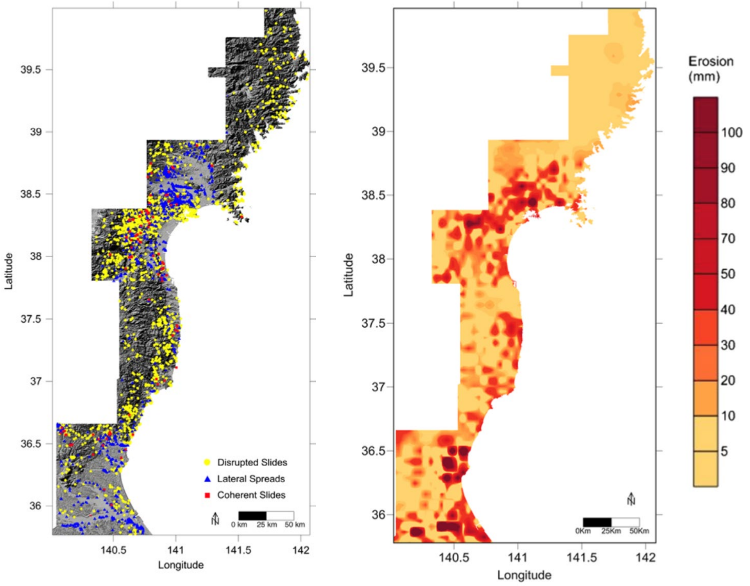
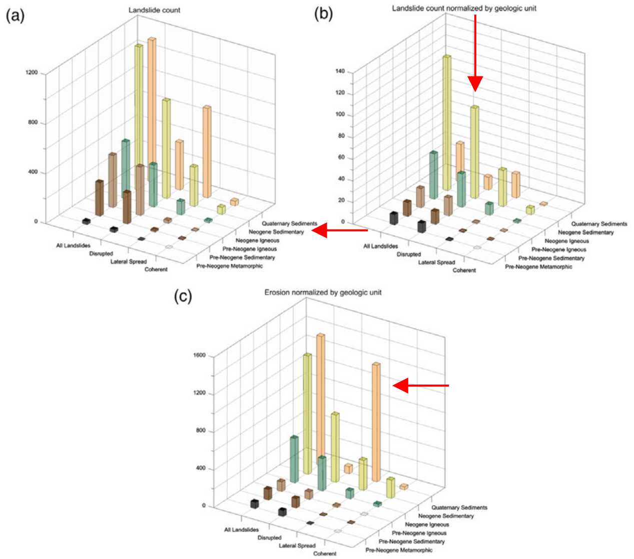
Landslides in Eastern Honshu Induced by the 2011 Tohoku Earthquake

by Joseph Wartman, Lisa Dunham, Binod Tiwari, and Daniel Pradel

Abstract In this article we discuss the character and spatial pattern of coseismic landslides from the eastern Honshu region of Japan, which was strongly shaken in the 2011 Tohoku earthquake. We developed a detailed geospatial database of 3477 landslides based on postearthquake field surveys and examination of high-resolution satellite imagery across a 28,380 km^2 landslide study area. Analysis of the database shows that a substantial majority (80%) of landslides occurred in Quaternary soil and Neogene rock units. Despite their abundance in the study area, relatively few landslides occurred in pre-Neogene rocks (i.e., older than 23 Ma). Further examination of the data showed that the most common types of landslides were (1) disrupted landslides in Neogene sedimentary rocks and (2) lateral spreading in Quaternary sediments. However, we found that coseismic landslide erosion (i.e., debris mobilization) was almost fully dominated by lateral spreading within Quaternary sediments. When comparing the landslide inventory with ground motions recorded by dense regional seismic arrays, we found no statistically significant correlation between landslide intensity and ground motion within the study area.

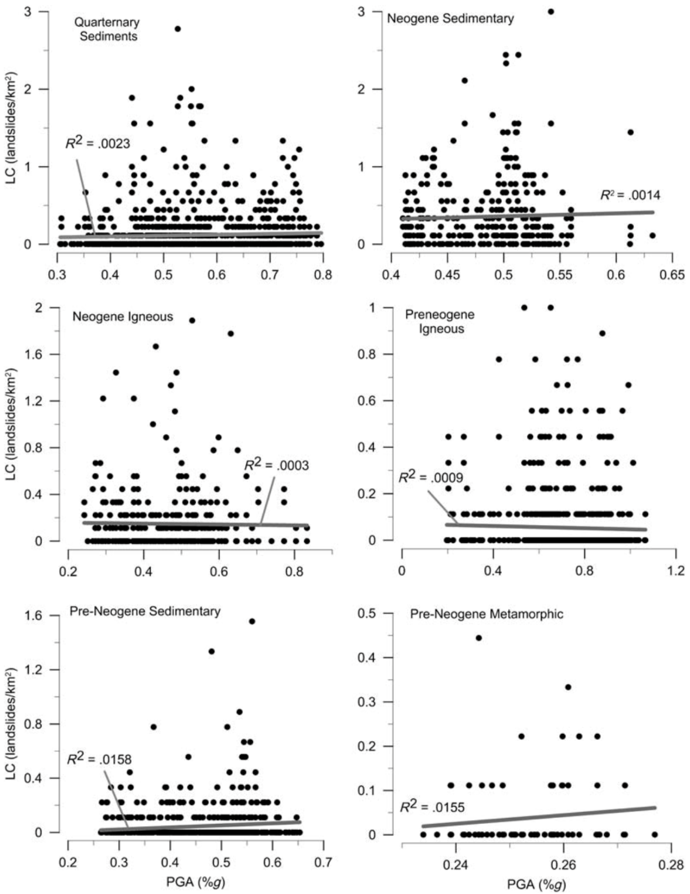
Online Material: Derivation of empirical parameters used in the area to volume transformations for lateral spreads.





- Most landslides occurred in younger geological units.
- Disrupted landslides in Neogene sedimentary units were common
- Landslide erosion was primarily driven by lateral spreading in Quaternary sediments
- *Overall, Neogene rock and Quaternary units dominated the landslide inventory*

2011 M9.1 Tohoku Earthquake



• Lack of Correlation Between Landslide Intensity and Ground Motion: Found no correlation between landslide intensity and PGA.

Other factors, such as the geologic unit, might have exerted a stronger influence on landsliding than ground shaking intensity.

• Unexpected Landslide Distribution: Despite experiencing high ground motions and having rugged terrain, the Kitakami and Abukuma Mountains had surprisingly few landslides. Conversely, the low-relief plain regions experienced a higher-than-expected level of landslide erosion.

Implications for Landslide Forecasting in Cascadia

1. Dominance of Young Geological Units

80% of landslides occurred in Quaternary sediments and Neogene sedimentary rocks, despite older pre-Neogene units' widespread presence.

Implication: PNW forecasting should prioritize mapping weaker/younger geological units as primary indicators of landslide susceptibility during subduction earthquakes.

2. Geological Controls May Outweigh Ground Motion

No statistically significant correlation between PGA and landslide concentration suggests geology is more important than shaking intensity as a predictive factor.

Implication: PNW forecasting should fully integrate geologic material and age, terrain factors, groundwater conditions, and anthropogenic modifications in addition to ground motion.

3. Lateral Spreading as a Dominant Coseismic Secondary Subduction Ground Failure Process

Lateral spreading, though fewer in number than disrupted landslides, accounted for ~90% of total debris mobilization and erosion in Japan.

Implication: PNW forecasting should emphasize lateral spreading hazards, particularly in low-relief/reclaimed areas like the Seattle waterfront, Portland river margins, and Columbia River basin.