CAUSES OF LANDSLIDES: CONVENTIONAL FACTORS AND SPECIAL CONSIDERATIONS FOR GEOTHERMAL SITES AND VOLCANIC REGIONS

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ABSTRACT

Geothermal sites and volcanic regions often exhibit significant landslide hazard. Such sites are typically characterized by sloping, hydrothermally-weakened saturated ground, and substantial seismic activity. Engineering works associated with geothermal sites, including wells, pipeline networks, and modification of ground by cuts and fills, also may contribute to landsliding.

Such landslides are always produced by a combination of processes and circumstances, although specific individual factors may dictate legal responsibility. Thus the causes of landslides can be subdivided into natural causes and those provoked by the works of man. Causes may also be classified into those which increase driving stresses within a slope, and those which decrease ground strength. Of the latter, the role of fluid pressure enhancement is paramount in reducing frictional strength. In geothermal areas, landslides of small to moderate-size are typical; these may be lethal, but are typically understood in terms of conventional geotechnical aspects. The gigantic volcanic landslides may also characterize geothermal areas; these are relatively infrequent, and are also less well understood in terms of cause-and-effect.

INTRODUCTION

Geothermal sites can exhibit significant landslide hazard. These sites often occur in areas of high relief, commonly on volcano flanks, and are typically located in zones of sustained seismic and sometimes magmatic activity, all of which can promote slope instability. Hydrothermal activity is ubiquitous and progressively weakens the rock mass, and construction activity or geothermal plumbing malfunctions can trigger landslides in the direct proximity of geothermal equipment and personnel.

Landslides affecting geothermal areas range from small movements of earth or rock to enormous slope failures involving large sections of a volcano, some ranking among the largest mass movements on Earth. The full spectrum of landslide types may occur, but for convenience most movements can be divided into block slides (translational) or slumps (rotational), which involve slow or episodic lateral movement, and unstable, mobile flows such as debris avalanches. Avalanches are characterized by the fast movement of large volumes of rock and debris fragments over low-angle slopes (Voight, 1978, 1979).

Gigantic volcanic landslides are relatively infrequent phenomena, although a handful of sizeable avalanches and slump-type events have occurred in the last century. These include avalanches accompanied by explosive volcanism at Mount St. Helens in 1980, Shiveluch in 1854 and 1964, Bezymianny in 1956, Harimkotan in 1933, Augustine in 1883, Oshima-Oshima in 1741, and Komatage in 1640. Avalanches accompanied by phreatic explosive volcanism occurred at Bandai and Ritter Island, both in 1888, Papandayan in 1772, and Iriga, probably in 1628. Numerous gigantic slumps and avalanches are recorded in the Hawaiian Islands, including the episodically active, magmatically-propelled flank of Kilauea volcano. Landslides unaccompanied by volcanism are also relatively frequent, such as the $34x10^6$ m^3 Ontake debris avalanche, Japan, of 1984.

Obviously such slope failures and associated explosions and water waves are hazardous, and during the last 400 years more than 20,000 people have been killed by avalanches and related events. Terrestrial Holocene avalanches of 1-10 km^3 in volume have travelled as much as 100 km and have affected areas as much as 1500 km^2 (Siebert et al., 1987). Some submarine landslides have been even larger, with volumes to 5000 km^3, travel distances exceeding 200 km, and affected areas as much as 23,000 km^2 (Moore et al., 1989). Avalanches may also cause catastrophic waves from interaction with oceans or lakes, and avalanche deposits may also impound hazardous, short-lived lakes.

However, it is important to realize that significant hazard is not restricted to extreme events. Fatalities and damage can occur with landslides of modest size, as illustrated by a slump-and-debris flow of ordinary proportions that in 1991 caused 33 fatalities at the Zunil geothermal field in Guatemala. For most geothermal areas it is the small or moderate-sized landslide that is of most influence, providing the higher-probability hazard.

CAUSES OF LANDSLIDES

Landslides are always produced by a combination of events or circumstances rather than any single process or cause, although in some cases a specific action -- perhaps dominant or perhaps trivial -- depending on whether or not the mass was already on the verge of failure, may set the mass in motion. This final action "triggers" the landslide movement, but is never the <u>sole</u> cause. An additional complexity is that a "trigger" may operate on the short-term, or with delayed action. Nor is the "trigger" process necessarily the cause that dictates legal responsibility. Whatever the causes, legal responsibility may also be attached to the recognition of, or the failure to recognize, conditions favorable to sliding or precursory symptoms of landsliding.

Given the inherent characteristics of the material and conditions, the causes of landslide initiation can then be divided into factors that produce an increase in shear stress, and factors that contribute to a reduction in shear strength. This is the approach of Terzaghi (1950; cf. Varnes, 1978). In some situations a given action may contribute simultaneously to both stress increase and strength decrease, but it is nevertheless useful to separate the physical components insofar as possible.

Inherent Causes

1. Initial composition.

2. Texture -- loose, weak materials are slide prone.

3. Bedding attitude relative to slope face.

4. Discontinuity systems--faults, joints, bedding planes. Bedding slip and fault slip history and orientation of movement.

5. Layering sequences in relation to strength and permeability.

6. Historic slope forming processes, colluvial slopes, movement history.

7. Initial physicochemical setting, conditions of weathering and alteration.

8. Historic seismicity.

9. Ambient (seasonal) groundwater conditions.

Causes that Increase Shear Stress

1. Removal of lateral or underlying support.
   a. Erosional processes producing or steepening natural slopes.
   b. Prior mass movements.
   c. Man-made excavations or removal of support.

2. Static Loading.
   a. Natural deposition -- slope or river sedimentation, tephra, lava.
   b. Weight added by natural precipitation.
   c. Man-made waste-piles, buildings, road fills.
   d. Weight of water from leaking pipelines, reservoirs, tunnels.
   e. Seepage pressures and cleft-water pressures from precipitation.
   f. Seepage or cleft-water pressures from man-influenced water sources.
   g. Magma pressure.
   h. Swelling pressures in expansion clays.

3. Dynamic loading.
   a. Earthquakes.
   b. Vibrations from volcanic explosion and eruptive processes.
   c. Vibrations from adjacent landslides.
   d. Man-made vibrations (blasting, machine, or pressure-line vibration).

4. Increase of surface slopes.
   a. Regional tectonics (slow or episodic change).
   b. Slope changes due to depositional processes.
   c. Man-caused slope change, engineered fills, dumps.
   d. Magma-intrusion-related deformation (cryptodomes).

Causes That Reduce Shear Strength.

1. Physicochemical factors.
   a. Weathering.
   b. Hydrothermal alteration.
   c. Softening of clays.
   d. Hydration of clay minerals.
   e. Ion exchange of clays.
   f. Solution of grain cement.
   g. Decomposition of organics in natural soils and fills.

2. Pore fluid pressure enhancement.
   a. Heavy rainfall or rapid snowmelt.
   b. Changes in groundwater flow regime.
   c. Base level change in reservoirs, lakes, or oceans.
   d. Thermal expansion of pore fluid due to frictional slip.
   e. Pore pressure changes in aquifers adjacent to magma intrusion, due to poroelastic deformation, thermal expansion, or separation of gas from rising magma.
   f. Vibration-induced pressure rise.
   g. Shear deformation-induced pressure rise.
   h. Consolidation seepage induced by surcharge.
   i. Man-influenced factors, involving reservoirs, stream, ditch, tunnel or culvert-blockages by fills, intercepts, diversions.
   j. Pipeline or well leaks.
   k. Frozen or blocked groundwater discharge zones.

3. Changes in structure

   a. Disturbance, remolding.
   b. Particle reorientation due to slip or dynamic loading; peak to residual strength loss.
   c. Fracturing and loosening of valley walls, stress relief, etc.
   d. Adjustments to groundwater flow paths; slope drainage enhanced, or impeded.

SLIDING AT GEOTHERMAL SITES

For small slides, the conventional geotechnical approaches adequately explain operational processes. The history of physiochemical factors such as hydrothermal alteration and base exchange may be particularly significant in reducing shear strength at geothermal sites. The conventional causes, such as fluid pressure enhancement related to precipitation or to the influence of man, are then superposed on the weakened material.

In some cases, causative factors related to landslides may operate more or less uniformly over an entire site. Thus in Equador in 1988 (Belloni and Morris, 1991), a regional earthquake created regional dynamic loading of slopes previously saturated by tropical rainstorms. The result was extensive landsliding over a vast region.

In other cases, the interaction of several factors may make selected areas more slide-prone than others. These interactions may be natural or related to activity by man. They may be obvious, subtle, or hidden (the latent defect). Identification of the hazard may require trained and experienced professional observation.

Cuts or fills may make certain locations within a project site more susceptible than others, even in relation to a regionally-uniform snowmelt or rainstorm. Conversely, the impact of a given storm may be magnified at specific locations by man-made diversions of ground or surface water fed by large drainage areas. Thus, as an example, a given project site may "feel the impact" of, effectively, a 25-year storm, although the regional rain gages record only a 2-year, 24-hour precipitation event. In this case the influence of the 2-year storm is not uniformly distributed over the region.

Given the significance of the role of pore pressure, wells, and pipelines and flowing springs at geothermal sites need to be carefully watched. Fluid leakages, perhaps at high pressure, may easily led to landsliding, and such landslides will almost certainly be located in the midst of personnel and critical facilities.

Ground subjected to slow (steady or episodic) creeping motions, due to a nearly-critical ambient balance of shear stress and strength, are especially hazardous. Such slow ground movements may stress, and eventually rupture, pipelines or wells. The resulting well or pipeline leaks can in turn create pore pressure rise and reduce shear strength, leading to substantial failure of saturated ground -- failure especially hazardous due to rapid motion and high mobility.

In addition, well-field construction activities involving cuts and fills may be factors in landslide causation, either directly in relation to increased loading, or indirectly in relation to a chain of water effects.

INTRUSIONS AND STABILITY

For the very large volcano sector movements on small slopes («10°), the mechanical problem has been incompletely resolved. In some cases a magmatic driving force is clearly involved; at Kilauea, for example, displacement and seismic events on the south flank take place soon <u>after</u> intrusive activity, indicating that the displacement is caused <u>by</u> forceful intrusion in the rift zones, and is not the cause <u>of</u> passive intrusion (Swanson et al., 1976). However, even this formidable driving force is insufficient to explain movements of a block kilometers thick and 10^2 km long on a flat slope.

The problem is partly analogous to the "overthrust problem" posed by structural geologists a generation ago (Hubbert and Rubey, 1959; Voight, 1976), and its proposed resolution is also similar -- in order to enable movement of a slide block of the appropriate dimensions, it is necessary to drastically reduce the frictional resistance of the basal slide plane. The most convenient way to do this is by enhanced pore fluid pressures in conjunction with the Terzaghi principle of effective stress.

The conventional means to establish pore pressure enhancement, by seepage flow, unusual precipitation, etc., are generally unsuitable for the great slides (Iverson, 1991).

The following mechanisms proposed for hydraulic pressure enhancement along the basal slip plane, and landslide instability, are related to magmatic intrusion (Voight and Elsworth, in press):

1. Pore pressure fields developed in poroelastic media around intruding dikes.
2. Thermal expansion of aquifer pore fluids by intrusions and (more especially) by eruption feeder dikes, with long-distance lateral pressure transmission within the aquifer (e.g., Delaney, 1982).
3. Degassing (boiling) of pressurized steam and other gases from rising magma, causing "steam-drive" pressure transmission in adjacent aquifers.

Thus the causative role proposed for magma intrusions is twofold, to increase the driving force, and to decrease the resisting force via fluid pressure enhancement. These mechanisms are not mutually exclusive; both may simultaneously exist at the same volcano complex. Pore pressures due to poroelastic deformation (Elsworth and Voight, 1992) may be more rapidly transmitted than that due to thermal expansion or degassing, but the latter processes may be longer lasting.

Earthquakes may be likewise influenced by the above processes; the intrusion-related hydraulic weakening mechanisms may enable seismic dislocation to take place over a wider fault area, thus enabling larger energy release than would otherwise be feasible (Faust and Voight, 1979).

Whether locally generated or of regional character, large earthquakes may trigger slide movements by augmenting the driving force, and may almost simultaneously reduce the resisting force via pore pressure enhancement. Similar effects can be produced by ground vibrations due to volcanic explosions or eruptions, whether phreatic or magmatic in character. Apparently such an event triggered the Papandayan debris avalanche of 1772, that killed about 3000 people. Papandayan is a prospect for geothermal development; remaining slope stability hazards are severe (B. Voight, unpublished data).

I consider these mechanisms as plausible explanations for the initiation of the gigantic landslides and sector movements, and related large earthquakes, of the Hawaiian Islands. They also seem reasonable as components for other intrusive-related landslide events, such as Mount St. Helens, Bezymianny, etc.

For the great submarine avalanches, long runout over the seabed requires an additional explanation; for this, I propose the sliding-consolidation model of Hutchinson (1986) and undrained loading of soft pelagic sediment.

MAGMA AND PORE FLUID PRESSURE

At Unzen volcano in Japan in 1792, a 0.34 km^3 avalanche was initiated about 80 days after the beginning of lava extrusion 3 km distant, on a separate peak of the Unzen complex (Siebert et al., 1987). Hot water emanated from the slide scarp (Ota, 1973). About 14,500 fatalities occurred in this event, mostly as a consequence of the avalanche-induced tsunami in the Ariake sea. It is reasonable to consider thermal- or exsolution-induced hydraulic gradients produced by the distant feeder dikes and related intrusives as a dominant "cause" of the avalanche.

Substantial pore fluid enhancement, as evidenced by pressure records and observations of flowing wells, have been documented at geothermal sites in Iceland at the Krafla geothermal complex (Elsworth and Voight, 1992; Stefánsson, 1981), and in the Westmann Islands (Björnsson, et al, 1976). Although landslides have not been produced at these sites (the topography is relatively flat), these observations document the importance of hydraulic effects at substantial distances (to 9 km) from the intruding magma.

ZUNIL LANDSLIDE: PARTLY INFLUENCED BY MAN?

The 1991 landslide at the Zunil field, Guatemala, illustrates the possible influence of geothermal development on landslide causation. Initially the media reported that a well blowout in the geothermal field triggered a landslide that killed 33 people. These reports appear to have oversimplified the situation.

A sketch map of the landslide suggests that well ZCQ-4 was centrally located within the region of slide initiation, roughly 130 m below the rear scarp (Flynn et al., 1991). The slide, which caused damage of the wellhead expansion spool, began as a slump and transformed into one major, and perhaps four subsidiary, successive and partly overlapping flow lobes of saturated clay-rich, hydrothermally altered debris. The lobe complex varied from 200 to 300 m wide, and travelled downslope as much as 800-1200 m, burying another geothermal well and the site of a proposed 15-MW power plant, destroying a church and at least 6 houses, and blocking a major regional highway.

In addition to the fatalities, many required treatment for burns from the hot mudflow. Slide volume was on the order of $10^6 m^3$, and thickness estimates range from 3 to 10 m.

Following the slide, well ZCQ-4 was blowing uncontrolled, and extensive efforts were required to plug it. It was ultimately repaired, and is now used as a backup well (A. Caicedo, cited by Hodgson, 1991). The utilization of well ZCQ-2 has also been impaired by the landslide, due to problems in siting the injection pipeline.

The landslide scar exposed a major trace of the Zunil fault zone (ZFZ), an important regional left-lateral strike-slip structure (Stoiber and Carr, 1973. Fumarole emissions are controlled by fault structures (parasitic, fractures, brecciation), resulting in a high degree of alteration, mainly kaolinite and alunite, with minor oxides, sulfate, and pyrite (Flynn et al., 1991).

The causes of this slide are, as usual, complex. The "inherent causes" include steep initial slopes (about 35 degrees), structural weakness related to the ZFZ, and intensive weakening of the ground by hydrothermal alteration. The seasonally variable, ambient groundwater conditions probably were significant. The rainy season extends from May through November, with annual precipitation about 900 mm. Piezometric heads related to surface water contributions were thus near maximum seasonal levels. However, precipitation during the rainy season was not unusual, and no rain is reported immediately prior to the landslide (Flynn et al., 1991, p. 431). Thus the above processes do not reflect the "triggering" agent. In addition to the above, the site may have had a previous landslide movement (D. Foley, 1992, personal communication), so that the slip plane may have been at near residual strength.

As regards "triggering" of the landslide, no unusual activities involving construction blasting or truck vibrations were reported immediately prior to the slide, and no significant earthquake activity occurred at the time of the landslide (Flynn et al., 1991). Such phenomena could have contributed to strength deterioration in the long-term, but apparently none of these were the "straws that broke the camel's back." Likewise, strength reduction due to progressive alteration would have been gradual.

Excavations associated with a mercury prospect and with geothermal access roads, and especially with construction of the well pad for ZCQ-4, may also have contributed since 1981 to an increase in shear stress, and to a stress-influenced acceleration of strength deterioration (creep-rupture). This argument is supported by the location of the well in relation to the landslide scar.

Apparently there is no evidence that a natural geothermal explosion or a well blow-out triggered a landslide (no explosion debris beyond slide limits, no eyewitness observations of pre-sliding explosions, etc.).

Saturation of the ground by (hot) water was undoubtedly a crucial factor in slide initiation (and also slide runout, where the high mobility may have been aided by hot mud of low viscosity). Nevertheless without detailed slope monitoring such details must remain obscure, as is the possible role of hydrothermal fluid in triggering slide initiation. Changes in hot spring activity may occur due to natural causes, and such changes have been cited as precursors to slope movements in Japan (Koide et al., 1963); alternatively the well casing may have leaked.

Of great significance are these facts: (1) A smaller landslide occurred behind ZCQ-4 on December 28, 1990, thus removing lateral support from the remaining slope (soil and rock falls previously occurred on several occasions in 1989 and 1990). (2) Spring flow had increased noticeably, with color changes, near the toe of the slope behind the wellhead, before the slide. Shortly before the slide on the evening of January 5, a "person watching water flow from the toe of the slope above the road labeled 'road to ZCQ-4'..."noted that the water 'became brown,' and then 'stopped completely." While he was enroute to report the latter development, the slide occurred (CyM-MKF, 1991).

To "geotechnically-aware" personnel these observations could have served as important warning indications for major slope failure. I believe that deformation monitoring would likely have disclosed significant, accelerating, slope movements. These accelerations could have been useful for more or less precise prediction of time of failure (Voight et al., 1989), although qualitative interpretation would have been sufficient for appreciation of the hazard.

The slope was gradually breaking up. The fractured, dilating toe sustained locally enhanced permeability, enabling an increase in spring flow; with continued slip, however, some groundwater routes were cut-off, causing the flow to "stop completely," and thus building up pore fluid pressures within the slope. At the same time, fine particles washing out of the slope (internal erosion) caused further deterioration of strength. Creep deformation near the toe of a moving slope also conceivably could have damaged the well casing; unpublished cross-sections suggest that slip surfaces associated with this slope may have intercepted the well at several levels. Any leak would have surely worsened stability.

These observations suggest that the slope in late 1990 was marginally unstable, with inherent causes including steep slope, fault-influenced strength, highly altered ground and alteration anisotropy, and seasonally-high groundwater. Prior slope movements may have weakened the slip surface.

No specific external short-term trigger such as earthquakes or road excavation occurred to cause failure on January 5. Instead, the ground seems to have been in a state of gradual but accelerating deterioration. The rate of deterioration may have become more severe following geothermal roadway and well excavations in 1981 (a delayed-action trigger). Adjustments in groundwater flow related to slope movement led to momentarily enhanced piezometric head on the slip surface, producing slope failure on January 5. But the evidence suggests that perceptible creeping movements of the slope occurred for at least one week (and likely much more) before slope collapse.

Thus Zunil is yet another case that demonstrates that, apart from slides generated by dominating external causes such as large earthquakes, landslides do not appear without warning.

CONCLUSIONS

Landslide causation is a complex subject, as all landslides are produced by a combination of circumstances. It is helpful to break down the causes into the inherent characteristics of the material and the site, and then to examine those factors which produce an increase in shear stress, and those which reduce shear strength.

Examination of these factors shows that geothermal areas may often have significant landslide hazards, and that a systematic approach to such hazards is warranted in order to save lives and protect facilities. Construction activity in geothermal areas can promote landsliding. Landslides do not occur without warning, apart from those triggered by earthquakes. But it is vital that such warning signs be recognized, and acted upon. It is painful to see loss of life where, in retrospect, precursory warnings seem abundant.

The amelioration or mitigation of landslide hazards is beyond the scope of this presentation, but approaches to these issues are thoroughly discussed in the literature. Certainly, for sites in which slope stability seems a potential problem, detailed hazard mapping, groundwater (and piezometric) assessment, and deformational monitoring offer useful approaches for investigation; the influences of construction excavation need to be evaluated; and slope stabilization schemes, such as drainage or surcharge placement, may need to be considered; and land-use zoning may be warranted.

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