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Debris flows caused by failure of fill slopes: early detection, warning, and loss prevention

Abstract This paper describes early detection, warning, and loss prevention for debris flows originating as failures of fill slopes. Worldwide, fill slopes constructed on steep terrain for roads, hillside residential developments, timber harvest landings, etc., are an increasing source of debris-flow hazards. Some fill failures that generate debris flows are the final stage of incremental failures that provide warning signs of instability in the months or years before the debris flow. Mapping and analysis of minor features, such as cracks and small scarps, on paved or unpaved surfaces of fills can identify incipient and impending fill failures that are major debris-flow hazards. Potential debris-flow paths can be mapped and risk assessments conducted. Loss prevention or reduction can be achieved by (1) prioritized maintenance, (2) prioritized repair, (3) monitoring, (4) warnings for emergency officials and the public, and (5) risk avoidance or reduction in land-use planning, zoning, cooperation between jurisdictions, and project development.

Keywords Debris flows · Fill slopes · Loss of life and infrastructure · Fill slope failure

Introduction

This paper focuses on (1) site-specific detection of incipient or incremental failure of fill slopes that are precursors to debris flows and (2) taking action to prevent loss of life and infrastructure. The purpose is to highlight the special opportunity for human intervention to avoid or reduce loss of life and property damage from one source of catastrophic debris flows: failure of fill slopes or embankments constructed on hillsides or mountainsides. Incipient or incremental failures of fill slopes at specific sites, such as along a mountain road, are detectable warning signs, such as arc-shaped cracks and scarps. The warning signs provide an opportunity to take action, such as maintenance, repairs, monitoring, determination of potentially affected people and infrastructure, and issuance of advisories or warnings.

Catastrophic debris flows can originate on natural slopes or constructed slopes (human-modified slopes). Understanding the origins of debris flows and identifying the source areas for future debris flows is important because debris flows have a long path of destruction that can extend hundreds or thousands of meters down slope from the source. The debris-flow source may be located on one property or legal jurisdiction, but the deaths, injuries, and infrastructure destruction may extend onto other properties or legal jurisdictions.

The literature on debris-flow hazards mostly examines debris flows originating on natural slopes and to a lesser extent on constructed slopes. When studies examine constructed slopes, the studies usually are case studies or investigations on the effect of human activities, such as timber harvest and roads, on debris-flow hazards. Whether assessing debris-flow hazards on natural or constructed slopes, previous studies often focus on landscape-level assessments of debris-flow hazards (e.g., Rollerson et al. 2001; Hofmeister and Miller 2002; Wieczorek et al. 2004; Salciarini et al. 2006; Wooten et al. 2007).

In contrast, this paper focuses on debris-flow hazards and risks associated with fill failures at a site-specific level. Worldwide, the debris-flow hazards associated with fill slopes are increasing. Humans construct and maintain fills and are responsible for the safety of fills. Humans can easily access and detect incipient or incremental fill failures that are potential catastrophic debris flows. As a result, humans can avoid or reduce loss of life and property associated with these site-specific hazards.

Worldwide increase in hazards and risks of debris flows initiated as fill-slope failures

Over the past 100 years, the worldwide increase in population at the base of mountains and in the construction on mountainsides (homes, roads, and other infrastructure) has created an increase in hazards and risks associated with debris flows originating on constructed slopes. As world population continues to grow, this trend of construction and human occupancy on steep terrain can be expected to continue. Construction for roads, housing developments, timber harvest, utility corridors, mining, and landfills are increasing the number of cuts (excavations) and fills on steep slopes (Fig. 1). Modern design and large construction equipment increase the size or volume of cuts and fills on steep slopes.

Some examples of the types of fills and hazards found in a few countries will help illustrate the problem. In an article on road-slope stability problems, including fill-slope failures, in Indonesia, Java, and other countries, Heath et al. (1990) note:

> In many countries, particularly in Southeast Asia where major roads are often constructed in very mountainous terrain, major problems involving slope failure can occur after the road has been opened to traffic. Within two to three years of construction the costs of dealing with such problems may, on occasion, exceed the original expense of building the road.

In Nepal about 86% of the area is steep hills and mountainsides. Sthapit and Tennyson (1991) report that fill failures are part of mass wasting in Nepal and "intensive use of the land resource for agriculture, grazing and fuelwood and development of infrastructure such as roads, without adequate conservation measures, has accelerated surface, gully and mass wasting erosion in Nepal."

In Japan and the west coast of North and South America, earthquakes as well as intense rain can trigger fill failures that result in debris flows and other types of landslides. In Japan, about

Fig. 1 Debris flows from fill-slope failures of road and log landing on Klamath National Forest near Happy Camp, California

75% of the area is mountainous. In Japan, urban development rapidly expanding from lowland to surrounding hills and mountains poses increasing risks of fill-slope failures and other geologic hazards (Iai et al. 2004; Kamai et al. 2005). In describing the interactions between land use and landslides triggered by the October 23, 2004 Niigata-Chuetsu Earthquake, Sidle et al. (2005) note:

> Roads, residential fills, agricultural terraces on hillslopes, and other earthworks increased the susceptibility of sites to slope failure. Numerous earthquake-induced failures in terraces and adjacent hillslopes around rice paddy fields occurred near Yamakoshi village...Clearly, land use activities in rural and urban areas exacerbated the extent of earthquake-triggered landslides.

The worldwide scope of fill-slope/debris-flow problem is reflected in other examples such as Hong Kong (Take et al. 2004), Malaysia (Lee and Pradhan 2007), Taiwan (Wu 2007), Europe, and the rest of the world (Cascini et al. 2005). As population and infrastructure increase around the world, the debris-flow hazards associated with fill-slope failures increase, and the risks to people and infrastructure increase. More people are moving into the base of mountains, or even constructing cut-and-fill housing developments (and associated roads) on the steep mountainsides. These areas, including alluvial fans, floodplains, and hillsides, may be subject to debris-flow hazards from both natural and human-modified slopes.

For example, the National Forests encompass 192 million acres in 42 states, including much of the mountainous terrain in the USA. The area along or near boundary between National Forests and the private land downslope is subject to wildland fire hazards where wildfire can spread from the forests to homes and infrastructure. In the 1990s about 8.4 million homes were built near National Forests and other federal lands, and this growth is continuing (US Department of Agriculture Forest Service and US Department of Interior 2005). These areas of increasing population along the base or lower slopes of the mountainous National Forests are also subject to geologic hazards, including debris flows (Fig. 1; Cloyd 2002; Collins 2005). Indeed, some debris flows are associated with the fire hazard (De la Fuente 2005; DeGraff et al. 2007). The National Forests manage more than 600,000 km (380,000 mi) of road, dominated by cut-and-fill construction in steep terrain. This vast road system (including log landings) includes debris-flow hazards associated with potential fill failures in many states across the USA. The US Forest Service recognizes the problems with road fill with unstable slopes, and has developed techniques to prevent and repair unstable slopes (Hall et al. 1994; Koler 1998; Musser and Denning 2005; Keller 2007).

Similar debris-flow hazards associated with roads and log landings are found in Canada, especially British Columbia. As the USA, Canada, and other developed countries reduce the area available for wood production over time, the acquisition of wood resources will shift, in part, to less-developed countries, where roads and log landings in mountainous areas will create more debris-flow hazards.

Nature of the hazard: debris flows originating as fill-slope failures

To illustrate the nature of the hazard of debris flows originating as fill failure, a few examples are presented.

1. Blue Ridge Parkway in North Carolina

   The scenic Blue Ridge Parkway (BRP) in North Carolina and Virginia is a two-lane paved highway located along mountain-tops where cut-and-fill construction on steep slopes is common. September 2004 Hurricanes Frances and Ivan triggered hundreds of landslides in North Carolina. Three road-fill failures on the Blue Ridge Parkway produced three major debris flows that gouged destructive paths downslope into the Grandfather Ranger District of the Pisgah National Forest in North Carolina.

   At BRP Milepost (MP) 349, the fill failure removed the outside traffic lane along a 27-m (89-ft) section of the Parkway above Licklog Branch. As the road fill traveled downslope, it scraped the thin colluvium and trees off of the steeply-dipping planar bedrock surfaces located on the steep mountainside below the Parkway. This "snowball effect" increased the volume and destructive power of the debris flow as it traveled downslope. The debris-flow initiation site (MP 349 fill failure) is at approximate elevation 1,411 m (4,630 ft). The debris flow traveled down the mountain and then down Licklog Branch for a distance of about 2,900 m (9,500 ft), terminating at approximate elevation 680 m (2,240 ft) near the junction with Curtis Creek (Fig. 2). Just a short distance away, at BRP Milepost 348, a similar road-fill failure initiated a similar debris flow with a long path (3,300 m; 10,800 ft) and similar elevation drop, from elevation 1,366 m (4,480 ft) on the Parkway down Bear Drive Branch to elevation 686 m (2,250 ft) on Curtis Creek (Figs. 2, 3, 4, and 5). At BRP Milepost 322 (Chestoa), a road-fill failure initiated the third major debris flow that traveled at least 900 m (3,000 ft) down the steep slopes of the Pisgah National Forest.

   In contrast with the BRP debris flows that initiated as fill-slope failures, on September 16, 2004, Hurricane Ivan triggered the Peeks Creek debris flow that initiated as a natural slope failure. The Peeks Creek debris flow destroyed 15 homes and killed five people. The debris flow originated at approximate elevation 1,341 m (4,400 ft) from a private land inholding within the Nantahala National Forest, traveled a path of approximately 3,219 m (10,560 ft), and terminated at approximate elevation 671 m (2,200 ft). The debris flow initiated as a failure of collu-

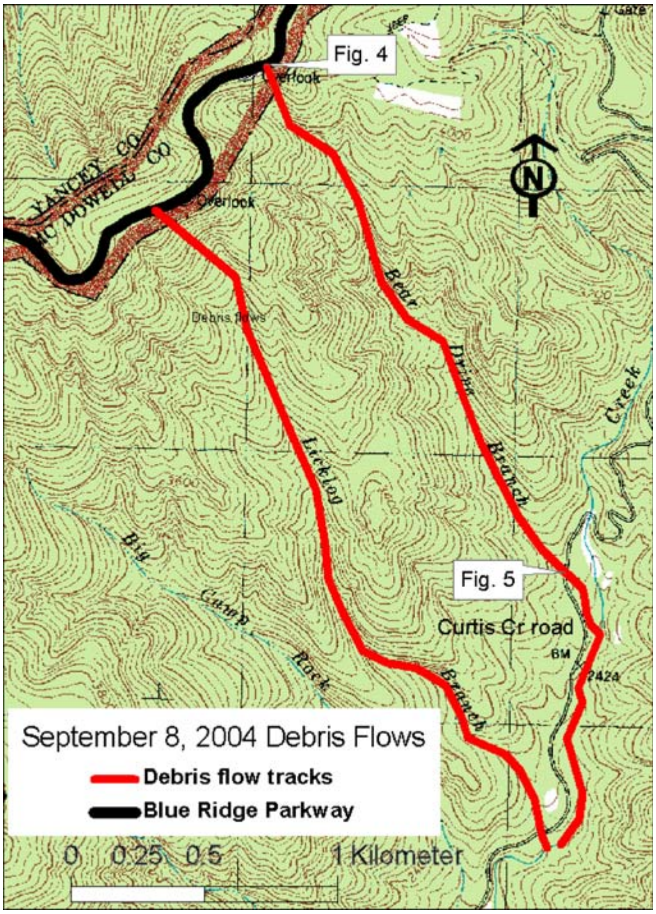

Fig. 2 Topographic map of Pisgah National Forest in McDowell County, North Carolina showing tracks of two debris flows originating as fill failures on Blue Ridge Parkway from September 8, 2004 Hurricane Frances

Fig. 3 Bear Drive Branch debris flow initiated at Blue Ridge Parkway fill-slope failure (Milepost 348) and traveled downslope 3 km (2 mi) across Pisgah National Forest, North Carolina (Hurricane Frances, September 8, 2004)

vium on a steeply-dipping planar bedrock surface (Wooten et al. 2007; Latham et al. 2005).

The Peeks Creek debris flow (initiating on a natural slope) and the BRP debris flows (initiating on a fill slope) are similar hazards. Each debris flow originated as failure of unconsolidated material on a steep mountain slope. Each debris flow initiated high on a mountain at similar elevations, providing great potential energy. Each debris flow scraped the thin colluvium and trees off of steeply-dipping planar bedrock surfaces, “snowballing” in volume and destructive power. Each debris flow had a major drop in elevation and a long path of destruction, extending hundreds or thousands of meters from the source area.

The September 2004 catastrophic failure of three road fills as well as partial failure of other road fills closed the Blue Ridge Parkway for months and cost millions in repairs. The resulting debris flows swept destructive paths downslope across the Pisgah National Forest watersheds. Cut-slope failures were relatively few and minor compared to fill-slope failures. A similar pattern was found in landslides triggered by the September 2004 Hurricanes Frances and Ivan on the Pisgah and Nantahala National Forests in North Carolina. Unpublished data (2005) by the author indicated about 68% of the landslides were road-related, primarily fill-slope failures that produced debris flows on steep slopes.

Fig. 4 Blue Ridge Parkway (Milepost 348) fill-slope failure that initiated Bear Drive Branch debris flow on Pisgah National Forest, North Carolina (Hurricane Frances, September 2004)

2. Logging road in British Columbia

After heavy rainfall and snowmelt, a debris flow occurred on May 31, 1997 in the Gowan Creek drainage about 80 km southeast of Pemberton, British Columbia. The following information on the Gowan Creek debris flow is based on a report by Bartle et al. (1997). The debris flow originated as a 100 to 200-m^3 (131 to 262 cubic yards) sidecast road-fill slope failure on a logging road in a timber harvest area (Fig. 6). The debris flow traveled downslope about 1,500 m (4,921 ft), dropping approximately 700 m (2,297 ft) in elevation from the fill failure to Gowan Creek. A timber faller working on the lower slope disappeared and is a presumed fatality of the debris flow.

Fig. 5 Impact of September 8, 2004 debris flow at Curtis Creek road more than 2 km downslope from initiation site at Blue Ridge Parkway fill-slope failure (Milepost 348). View downstream to bridge crossing of Bear Drive Branch on Pisgah National Forest, North Carolina

Fig. 6 May 31, 1997 Gowan Creek debris flow initiated as failure of road-fill slope about 80 km southeast of Pemberton, British Columbia (Bartle et al. 1997)

The debris flow scoured and moved an estimated 61,000 m^3 (80,000 cubic yards), of which 22,0000 m^3 (29,000 cubic yards) was deposited along the margins of the track and at the base of the mountainside, and 39,000 m^3 (51,000 cubic yards) entered Gowan Creek.

The section of road fill that failed was 17 m (56 ft) wide with a volume of 100 to 200 m^3 (131 to 262 cubic yards). But this modest-size fill failure initiated a major debris flow of 61,000 m^3 (80,000 cubic yards). This quantifies the "snowball effect", in which the volume and destructive power of the debris flow is cumulative as it travels downslope. Hungr et al. (2005) provide a review and analysis of this important factor (entrainment of material) in determining the magnitude of debris flows.

The fill failure initiated the debris flow on a smooth steeply-dipping (30–34°) granitic bedrock surface overlain by 0.5 m (1.6 ft) of till and 1.5 to 3 m (5 to 10 ft) of road fill. As the debris flow moved downslope, it scraped the thin colluvium (0.5–1 m; 1.6 ft 3.3 ft) and trees off of the steep bedrock surfaces and widened its path on the mountainside. Like the Blue Ridge Parkway debris flows, this debris flow initiated as a sidehill fill-slope failure, not in a channel; however, the end result of the debris flow scraping off the colluvium and trees was the creation of a channel incised into the mountainside (Fig. 6). When massive debris flow entered Gowan Creek, it may have temporarily dammed the stream. The potential for debris flows to create temporary dams that can also fail is another way, in addition to the snowball effect, that the destructive power of debris flows can be magnified.

The investigation of Gowan Creek road-fill failure found significant cracks in the road fill next to the failure and concluded that the failed section was likely fractured (cracked) prior to failure. The investigation report (Bartle et al. 1997) noted that "settlement and tension cracking of the roads surface and fills…is a common precursor to road failure. Road-fill failures typically result in debris slides involving a few hundred to perhaps a thousand cubic metres of material. When such failures occur upon moderate to steep slopes they may trigger debris flows similar to the recent event at Gowan Creek."

The investigation report (Bartle et al. 1997) concluded that (1) a field inspection prior to the fill failure would have detected indicators of potential slope instability, such as cracking and slumping in the road fills, and (2) if the road had been maintained and/or deactivated to current standards, it is probable the Gowan Creek debris flow would not have occurred.

Log landings are another type of construction associated with roads in timber harvest area in USA, Canada, and elsewhere in the world. Construction of log landings may leave fill or sidecast perched on a steep slope. Timber harvest operations may add woody debris to the top or sides of the fill or sidecast. The mass of unconsolidated material at log landings can be much larger than road fills. Failure of fills, sidecast, and woody debris at log landings can trigger debris flows (Figs. 1 and 7).

3. Road fills at stream crossings

In addition to sidehill road fills, road fills that span stream channels (perennial, intermittent, ephemeral) are another major source for initiating debris flows. In steep terrain, road fills at channel crossings are, at best, an engineered fill with a culvert or other structure to allow water and bed load to pass downstream. At worst, the road fills, during intense rainstorms, are a nonengineered dam with no spillway. Some culverts cannot accommodate storm flows, particularly with significant bedload transport or large woody debris. The load transport during storms can block or plug a culvert and turn the fill into a dam. This action can potentially lead to a failure of the fill (dam) and turn the storm water and earthen fill into a debris flow (Fig. 8).

Fig. 7 Debris flow initiated as log-landing fill failure, Vancouver Island, British Columbia. Photo: Gino Fournier

Site-specific vs landscape-level assessment of debris-flow hazards

Studies of debris-flow hazards usually focus on debris flows originating on natural slopes. Many studies use past debris-flow events to identify the type of terrain most susceptible to debris flows (e.g., Rollerson et al. 2001; Hofmeister and Miller 2002; Salciarini et al. 2006; Wooten et al. 2007). The studies look for

Fig. 8 Stream crossing fill failure initiates debris flow. Note broken culvert plugged with bed load (Klamath National Forest, California)

factors that are associated with occurrence of debris flows on natural slopes, such as slope gradient; geologic materials and structures; depth of regolith; characteristics of colluvium; presence of hollows; groundwater levels; and past occurrence of debris flows. Some factors are then used to develop a model to map the landscape into potential for debris-flow hazards. The hazards usually identified are the potential for debris flows from natural slopes. The debris-flow hazard map may show for a broad landscape (tens to hundreds of square kilometers) the susceptibility or potential for debris flows. The source areas for debris flows (for example, high-elevation hollows in the headwaters of mountains) often are remote and not easily accessed.

When studies examine constructed slopes, the studies usually are case studies or investigations of the influence of roads on debris-flow occurrence. The studies typically assess the effect of human activities, such as timber harvest and roads, on debris-flow hazards. Such information may then be used to refine a model to map the landscape into potential for debris flows. Whether examining debris flows on natural or constructed slopes, previous studies generally focus on landscape-level assessments of debris-flow hazards (e.g., Rollerson et al. 2001; Hofmeister and Miller 2002; Wieczorek et al. 2004; Salciarini et al. 2006; Wooten et al. 2007). Landscape-level assessments provide a coarse filter for managing debris-flow hazards.

In contrast, this paper focuses on site-specific detection of debris-flow hazards from incipient or incremental failure of fill slopes on existing roads, hillside developments, log landings, etc. on steep slopes. Site-specific assessments provide a fine filter. This paper also focuses on actual rather than potential instability, that is, early-stage failure (incipient) and incremental failure of fills. The importance of scale in landslide risk is reviewed by Parson et al. (2007).

Single vs multiple (incremental) fill-failure events; detectable vs nondetectable warning signs

Debris flows originating from natural slopes and fill slopes can be divided into four categories based on single vs multiple (incremental) failure events and detectable vs nondetectable warning signs (e.g., tension cracks and scarps).

1. Natural slope—single-failure event: sudden slope failure produces debris flow. No warning signs are detectable in natural slope before the debris-flow-triggering event.
2. Natural slope—multiple-failure event (incremental failures over time) leads to sudden failure that produces debris flow. Warning sign(s) are detectable in natural slope before debris-flow-triggering event.
3. Fill slope—single failure event: sudden fill-slope failure produces debris flow. No warning signs are detectable in the fill slope before the debris-flow-triggering event.
4. Fill slope—multiple failure events (incremental failures over time) leads to sudden failure that produces debris flow. Warning sign(s) are detectable in fill slope before debris-flow-triggering event.

This paper focuses on the fourth category: incipient or incremental failures of fill slopes with warning sign that are detectable in the days, months, or years before initiation of a debris flow. When fill failures initiating debris flows occur, postevent interviews with road maintenance crews often turn up the fact that the fill had been a trouble spot in the past, showing signs of incremental failure that required patch paving, fill repairs, or road grading.

Early detection of fill instability and incremental failure

Some fill failures that generate debris flows are the final stage of an incremental fill failure that displays warning signs of instability in the days, months or years before the debris flow. Early detection, mapping and analysis of warning signs (subsidence, tension cracks, small scarps, grabens, and slumps) on paved or unpaved surfaces of fills can identify incipient and impending fill failures that are major debris-flow hazards.

When a road-fill slope collapses completely and moves down slope as a debris flow, the upper edge of the failure forms an arc-shaped main scarp (Fig. 4). Knowing the general shape and extent of typical fill failures allows early detection of incipient or incremental failures. Field reconnaissance of cracks or scarps indicates a discrete mass of fill may be detaching from the hillside. The initiation of a fill failure may first appear as a crack or series of discontinuous cracks that outlines an arc-shaped area of fill (Fig. 9). Over time, tiny scarps (a few centimeters or less in height) may develop, indicating increasing instability of the fill (Fig. 10). Occasionally, as tension cracks or scarps expand, an elongate depression (graben) in the road bed or fill surface may develop (Fig. 11).The initial cracks and tiny scarps are easy to detect on paved roads; when maintenance crews apply crack sealant or asphalt patches, the evidence of these initial instabilities is preserved in the pavement and easily recognizable (Fig. 17). The

Fig. 9 Arc-shaped tension cracks in road fill on Blue Ridge Parkway near Mount Mitchell, North Carolina (August 1, 2005)

Fig. 10 Arc-shaped tension cracks in road fill on Blue Ridge Parkway south of Linville Falls, North Carolina (August 3, 2005). Photo: Scott Eaton and Bob Sas

Fig. 12 Incremental failure evidence with asphalt patching in road fill on Blue Ridge Parkway north of Mount Mitchell, North Carolina (August 2, 2005)

initial cracks and tiny scarps are more difficult to detect on gravel or unpaved roads because traffic, storm run-off, and road graders wear away the cracks and tiny scarps. Thus, it is important that maintenance crews or geotechnical staff photograph the cracks and scarps before road graders level up the road surface and remove evidence of the instability.

Over time, the incremental failure of the fill may continue as small settlements that require repeated asphalt patching (or road grading on unpaved roads; Fig. 12). In some cases, the incremental failure of the fill may accelerate and result in one of more large slumps (several centimeters to meters or more) that require road closure until the fill is repaired (Figs. 13 and 14).

Each occurrence of new or renewed activity (cracking, scarp development, slumping) is a fill-failure event. Incremental failure of the fill involves one or more of these partial failure events that ultimately may lead to a total failure that initiates a debris flow. An incremental failure may not go through all stages of failure: subsidence, tension cracks, small scarps, larger scarps and slumping. For example, tension cracks may be the only warning sign that precedes a total failure that initiates a debris flow.

Incremental failure does not always lead to total fill failure and initiation of a debris flow. A fill may undergo various stages of partial failure but never reach the point of total fill failure. For example, the intensity or duration of rainfall needed to trigger total fill failure may never occur. However, incremental failure is evidence of instability and a potential for total fill failure. So, it is prudent to detect these warning signs and to monitor and take action when appropriate.

Maintenance crews are the frontline resource for early detection of warning signs of road-fill failures. When present, the geotechnical staff needs to communicate and collaborate with the road maintenance staff in developing the detection and reporting system. The geotechnical staff can provide the training to emphasize the importance of detecting, inventorying, and reporting features suggestive of incremental or imminent failure. A camera, measuring tape, notebook, and Global Positioning System (GPS) are all that is needed to inventory the warning signs.

When maintenance crews identify warning signs, it is important that the geotechnical staff receive prompt notice so that the activity

Fig. 11 Graben in road fill on Blue Ridge Parkway south of Linville Falls, North Carolina (August 3, 2005). Photo: Scott Eaton and Bob Sas

Fig. 13 Slump in road fill on Blue Ridge Parkway (MP345) north of Mount Mitchell, North Carolina (January, 2005). For scale, note person standing on slump below road

Fig. 14 Slump in road fill on logging road in Klamath National Forest, California

can be assessed and, if appropriate, action taken (advisories, warning, maintenance, repairs). The geotechnical staff also can conduct periodic detection of warning signs (e.g., once a year). Periodic field surveys by geotechnical specialists are fundamental to a sound detection and warning program. It also is an opportunity to provide feedback to, and coordinate with, the maintenance crews on their detection work.

The road-pavement-condition surveys conducted by highway departments can serve a dual purpose by providing data for early detection of incremental fill failure. Sas and Eaton (2006) provide an example of using a video-recorded pavement survey for reconnaissance of incremental fill failures. The Federal Highway Administration recorded a video pavement survey (VisiData) for a section of the Blue Ridge Parkway in North Carolina prior to September 2004 Hurricane Frances. The VisiData shows evidence of pre-existing failure (mostly cracking) prior to September 2004 BRP fill failures that initiated debris flows onto the National Forest (R.J. Sas, personal communication, 2007).

Warnings

Early detection of fill failures can provide three types of warnings:

1. Type 1: Warning signs of unstable fill activity (Fig. 15), such as:
    - a) Subsidence
    - b) Tension cracks
    - c) Small scarps (less than a few centimeters)—passable by passenger car and may not require road closure prior to repairs
    - d) Slumps (large scarps)—not passable by passenger car and requires closure of traffic lane or entire road for repairs
    - e) Graben
    - f) Patched road pavement (including signs of repeated patching)

These features are warning signs of fill activity that indicate incremental fill failure. The key point is that these are site-specific warning signs identifying fill instability on a specific section of road. These features are actual, not potential, instability. Cracks and scarps are important because: (1) they are a path for water to infiltrate the fill, (2) they are evidence that the fill mass is detaching from the hillside or mountainside, and (3) they indicate a potential for more slippage. Warning signs can be detected in paved or unpaved roads.

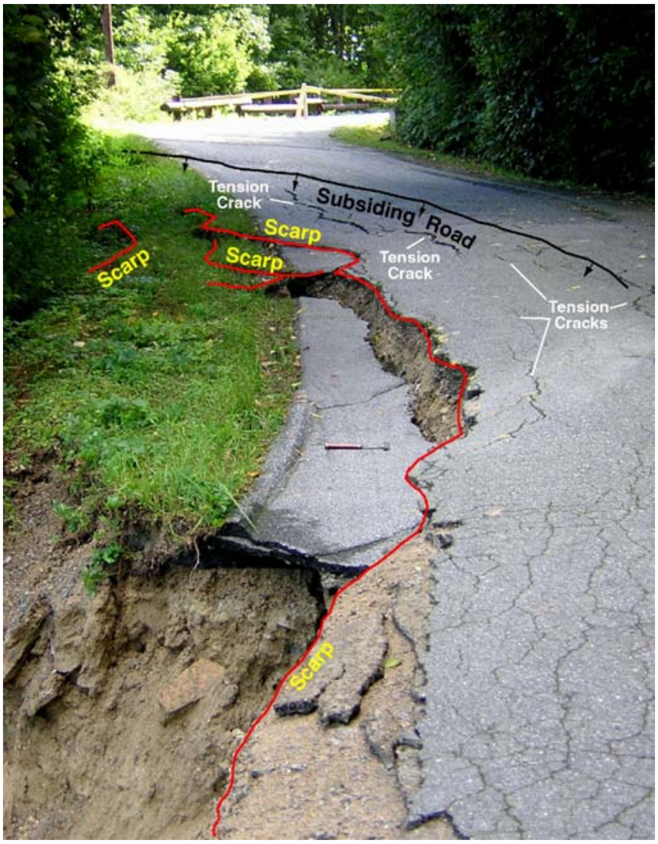

Fig. 15 Warnings signs of unstable fill (subsidence, tension cracks, scarps). *Lower left corner* of photo shows major scarp of road-fill failure that mobilized into a debris flow from heavy rain remnants of Hurricane Francis in 2004 in Bear Rock Estates subdivision, Henderson County, North Carolina. Photo: North Carolina Geological Survey

Road fills at stream channel crossings have additional warning signs, such as (1) culverts that require unplugging of bed load or removing woody debris blockage of inlet, (2) culverts that are broken or corroded, and (3) evidence or records of overtopping of fill during a rainstorm, indicating the fill became a temporary dam. Maintenance records or interviews with maintenance personnel are other sources for these types of warning signs.

2. Type 2: Warning to owners and/or managers of the fill (road fill, home site fill, fill at log landing, etc.)

    Early detection and analysis of the warning signs at a specific fill may indicate instability and incremental fill failure with potential for ultimate collapse and initiation of a debris flow. Because it is a specific site, a hazard and risk assessment can focus on the consequences of a potential debris flow on people and infrastructure downslope from the fill. The path or track of a debris flow initiated by a fill-slope failure can be estimated and mapped using similar techniques to estimate and map the path of a debris flow initiated as a natural slope failure. Various techniques for mapping the track of potential debris flows are available (e.g., Hungr 1995; Fannin and Wise 1995; Finlay et al. 1999; Hunter and Fell 2003; Wooten et al. 2007).

    When the findings of the hazard and risk assessment warrant concerns, they can be presented to the owners and/or managers of the fill. The findings serve as warnings of the consequences of potential debris flows associated with specific fills. The findings also provide the owners and managers a basis or justification to take action. These actions to mitigate hazards or reduce risks will be discussed in "Loss prevention."

3. Type 3: Warning to potentially affected people downslope from the unstable fill

   When the owners and/or managers of unstable fill are aware of the hazard and risks to people and infrastructure downslope from an unstable fill, then warnings or advisories can be provided to potentially affected people. The projected path or track of a potential debris flow will help identify the people and infrastructure at risk. Debris flows initiated as fill failures high on a mountainside can have a destructive path length of hundreds or thousands of meters. Often, the people and infrastructure at risk are located on alluvial fans or floodplains at the base of hills or mountains. The path or track may cross two or more jurisdictions and impact public and private lands. Warnings or advisories will be discussed in "Loss prevention."

Loss prevention

Early detection of incremental fill failure at specific sites provides an opportunity for loss prevention or reduction from potential debris flows. Once the risk assessment has identified these sites, then the following steps can be taken to reduce or prevent loss:

1) Prioritized maintenance

   Identification of hazardous, high-risk fills can be used to set priority for maintenance work. When a fill shows cracks, scarps, and other evidence of instability, one cause of the instability may be related to maintenance (or lack of maintenance). For example, if a road culvert tends to plug up and overflow stormwater into a fill, it may cause the fill to become unstable (Fig. 16). Thus, when cracks or other warning signs of instability identify a hazardous, high-risk fill, then maintenance of a culvert near this fill may be a higher priority than other culverts.

   State, federal, and county road departments with limited funds find it impossible to do all maintenance on all roads every year. Agencies must set priorities for road-maintenance work. The geotechnical staff can help the maintenance staff set priorities by identifying the hazardous, high-risk fills.

   Identification of hazardous, high-risk fills also can help change maintenance practices that adversely affect stability of fills. When fill on a paved road settles or slumps, the maintenance crew usually applies asphalt to restore a level driving surface (Fig. 12). Often, these sections of road fill will continue to settle every few years, and maintenance crews will apply asphalt every time. Repeated patching can accumulate to 1 to 3 m (3 to 9 ft) of asphalt on top of the fill (M.W. Weber, personal communication 2007). The repeated patching adds more weight to the fill and increases the instability. Similar processes occur on unpaved or gravel roads, where spot gravel patching or backfilling is used to level and smooth the road surface over a section of settling or slumping fill (Fig. 14). If this maintenance practice is used on hazardous, high-risk fills, it may increase the chance for a total fill failure and destructive debris flow. To prevent this problem, the geotechnical staff can provide training for, and develop a close working relationship with, the maintenance staff. These two staffs working together can change maintenance practices that aggravate unstable fills.

2) Prioritized repair

   Repairs are aimed at correcting repetitive and costly maintenance problems or at reopening a road or other facility closed by rainstorms, hurricanes, landslides, earthquakes, or other emergency events. Identification of high-hazard, high-risk fills can be used to set priority for repairs of chronic or acute maintenance problems.

   For these fills, it is important that the geotechnical staff also be fully involved in developing remediation alternatives and design.

   For example, a hurricane or other large rainfall event may trigger cut-slope and fill-slope failures that require major and minor repairs. In the case of fill slopes, the hurricane may have triggered a wide range of instability at fills, from renewed movement at pre-existing unstable fills to new movement at previously stable fills. The geotechnical staff can (1) assess the posthurricane instability and potential for fill failure to produce debris flows (hazard assessment) and (2) conduct a risk assessment of potentially affected people and infrastructure. The geotechnical staff's identification of high-hazard/high-risk fills can help set priorities for emergency repairs. Setting priorities is especially important when a disaster situation or recovery effort is threatened by more rainfall or more earthquake activity. In conducting a postdisaster assessment of fills showing various degrees of failure (cracks, scarps, slumps), geotechnical staff can be used to determine factors of safety or other stability parameters (Hall et al. 1994; Turner and Schuster 1996). Recent work by Wu (2007) focuses on evaluation of fill-slope stability and prediction of rainfall-induced fill-slopes failures.

   In addition, the pressure to reopen roads closed by a disaster can foster a tendency to adopt the quickest and cheapest repairs, which in the case of a slumped fill may be to add more fill on top of the slumped fill. The added weight of more fill may be sufficient to cause a total fill failure and debris flow in the next heavy rain or earthquake. However, if the geotechnical staff conducts a high-hazard/high-risk assessment of slumped fills, then short-sighted repairs may be averted in favor of more stable repairs.

Fig. 16 Plugged culvert creates two fill-slope debris-flow hazards: (1) a temporary dam at the plugged culvert, and (2) overflow leading to failure of another fill. Road in Klamath National Forest, California

Various remediation techniques are available to repair or mitigate unstable fills, such as:

1. Stabilizing the fill using soil nails.
2. Buttress.
3. Retaining walls.
4. Reinforced earth.
5. Deep patch road embankment repair (Musser and Denning 2005).
6. Improved surface and subsurface drainage in the fill.
7. Replacement of corroded or broken pipe in fill.
8. Lightweight fill material.
9. Sag the vertical grade.
10. Remove the fill from the slope and shift the horizontal grade into the cut-slope.
11. Benching the lower part of fill into bedrock.
12. Deep-rooted vegetation.
13. In extreme cases, bridge over the fill failure.
14. In extreme cases, major relocation of the road section with the fill failure.

Overviews of remediation techniques for unstable cut and fills with emphasis on roads in mountainous terrain are available (e.g., Hall et al. 1994; B.C. Ministry of Forests 2001; Keller and Sherar 2003; Keller 2007). In addition, sometimes the solution to unstable fills involves (1) repairs to other elements of the roads that are causing the fill failure, such as undersized culverts that plug and send stormwater into the fill (Fig. 16), or (2) remediation of the geologic foundation conditions underlying the fill (such as wet weather springs, soft or weak geologic foundation materials, etc).

Because this paper focuses on early detection and loss prevention, it is worth noting that the techniques, such as launched soil nails, that allow stabilizing a fill in the early stages of incremental failure, are extremely important. By repairing the problem early, the need for repeated and more costly repairs is avoided, and the hazard to people and infrastructure is abated. Weber et al. (2005) show before-and-after conditions of fill stabilization using soil nail launchers in Summit County, Ohio (Figs. 17 and 18). Barrett (2006) describes recent innovations in soil nail technology and other fill-stabilization techniques.

Fig. 17 Highland road fill before stabilization with launched soil nails, Summit County, Ohio. Note asphalt patch preserving evidence of incipient fill failure. Photo: Weber et al. 2005

Fig. 18 Highland road fill after stabilization with launched soil nails, Summit County, Ohio. Photo: Weber et al. 2005

When roads are closed or decommissioned, the geotechnical staff can conduct hazard and risk assessments and provide recommendations, such as partial or full road-fill pullback, to deal with incremental fill failures (B.C. Ministry of Forests 2001).

3) Monitoring

Once fills with warning signs of fill-failure/debris-flow hazards have been identified, it is important to monitor these fills for signs of increasing instability and incremental fill failure. Several types of monitoring can be implemented. Monitoring does not require expensive equipment. Equipment already available (camera, tape measure, notebook, and GPS) will suffice for routine monitoring of warning signs.

Maintenance crews are the frontline resource for detecting and monitoring warning signs. The geotechnical staff and maintenance staff can develop a system for the maintenance crews to monitor the hazardous fills and to report new cracks, scarps, or renewed activity on pre-existing fill failure features. When maintenance crews identify new or renewed activity, it is important that the monitoring system promptly notify the geotechnical staff so that the activity can be assessed and, if appropriate, action taken. Possible actions include maintenance, repairs, and public advisories and warnings.

The geotechnical staff can conduct periodic monitoring, e.g., once a year. The monitoring by geotechnical specialists is fundamental to a sound program of loss prevention. In addition, it provides an opportunity to provide feedback to, and coordinate with, the maintenance crews. Scenic overlook fills are larger fills than typical road fills and, thus, deserve careful hazard/risk analysis and monitoring when signs of fill distress are discovered (Fig. 19).

Another type of monitoring could occur before, during, and/or after intense rainfall or snowmelt that may trigger new or renewed fill-failure activity. Ideally, this monitoring would be a combined effort by the maintenance and geotechnical staff. Monitoring before or during a storm may provide timely information needed to issue public advisories or warnings and to perform some corrective action, such as unplugging a culvert, that may avert a catastrophic fill failure. Based on a

Fig. 19 Grass in cracks and curb separation in scenic overlook (fill) on steep slope on Blue Ridge Parkway in North Carolina: signs of long-term movement of fill appropriate for hazard/risk analysis and monitoring

previously developed risk assessment, some high-hazard, high-risk fills may warrant monitoring during a storm.

Postearthquake inspection and monitoring is another valuable tool because earthquakes can trigger new or renewed fill instabilities. For example, Wartman et al. (2003) report that the June 23, 2001 earthquake in Peru triggered road damage that was typically along the shoulders or edges of the roadways, such as the Pan American highway (Fig. 20). Hazard and risk assessment of these fills can be used in (1) prioritizing and designing fill repairs, (2) determining the need for public advisories or warnings, and (3) including the fills in a monitoring program.

4) Warnings for emergency officials and the public

Loss prevention is focused first on public safety. Federal and state agencies are working to increase public awareness and education about debris-flow hazards. For example, the US Geological Survey (USGS) published a "Debris-Flow Hazards in the Blue Ridge of Virginia" fact sheet to inform the public about debris hazards and provide safety tips (Gori and Burton 1996). Public awareness is a foundation for issuing effective advisories and warnings.

The National Weather Service provides forecasts of approaching intense storms. Based on research on rainfall intensity/duration thresholds that have triggered debris flows in particular geographic regions (Wieczorek et al. 2001; Wilson 2003), the USGS has started to issue landslide warnings for these US regions based on weather-service forecasts. Jakob et al. (2006) proposed a landslide-warning system based on rainfall thresholds for use in forest-operation shutdowns on the north coast of British Columbia. These types of landslide advisories help the public and emergency officials to be alert for debris flows and to take appropriate actions. The landslide warnings provide a landscape-level warning.

The next level in public warning is site-specific warnings. The early detection of unstable fills with a high potential for debris flows and a high risk to people and infrastructure provides the basis for site-specific advisories or warnings. The owners or managers of high-hazard/high-risk fills can inform local government officials and potentially affected people of these site-specific debris-flow hazards.

The owners or managers of high-hazard/high-risk fills may participate in two types of public advisories or warnings. The method for delivering these advisories or warnings would best be designed in cooperation with local officials. First, there is an initial advisory or notice to potentially affected people when the risk is first identified in nonemergency period. For example, when routine inspection of an earth-fill dam or a mine-waste pile discovers signs of an incremental failure, local officials deliver an initial advisory to specific homeowners that their home is in the path of the potential flood or debris flow. In a similar way, when a high-hazard/high-risk road fill or residential fill is discovered, local officials can deliver an initial advisory to specific homeowners that their home is in the path of a known debris-flow hazard.

The second type of warning is an emergency warning to potentially affected people. For example, in the case of a weather forecast of torrential rains, local officials can deliver an emergency warning of potential failure of a high-hazard/high-risk fill. This warning is site-specific in regard to a specific fill and a specific downslope community at risk. A landscape-level landslide warning, such as a USGS-issued landslide warning for a state or region, can become the trigger for local officials to issue site-specific debris-flow warnings for high-hazard, high-risk fills.

5) Risk avoidance or reduction by land-use planning, zoning, cooperation between jurisdictions, and project development.

(a) Land-use planning and zoning

The worldwide increase in population and development at the base of mountains and on hill slopes has increased the risks associated with debris flows originating on constructed slopes and natural slopes. Perhaps the greatest opportunity to prevent loss due to debris flows from fill slopes as well as natural slopes is risk avoidance or reduction through land-use planning and zoning. For example, high-density residential development could be prohibited in high-hazard zones, while allowing open-space

Fig. 20 Partial failure of fill slope on Pan American highway near the town of Tambillo, Peru, June 23, 2001 earthquake damage (Wartman et al. 2003). Photo: US National Science Foundation-sponsored geotechnical reconnaissance team

uses such as parks or golf courses in such zones. Zoning could also include construction codes requiring geotechnical assessments prior to construction on steep slope or debris-flow zones. However, land-use planning and zoning are difficult, time consuming processes that require interagency cooperation and resolution of thorny social, economic, political, and public issues. Kamai et al. (2005) point out the difficulty of instituting zoning even when landslide hazards are well known.

The geotechnical community can provide the technical information about debris-flow hazards to help the public and government officials in the development of land-use plans and zoning (Hinkle and Mills 2002; Wooten et al. 2007). The more site-specific assessments of debris-flow hazards associated with incremental failure of fill slopes discussed in this paper can help by (1) showing real, accessible hazards and warning signs that the public and government officials can see with their own eyes and (2) showing that accessible hazards can be mitigated not just by risk reduction (planning and zoning) but also by hazard reduction (construction codes for new fills and remediation for existing fills).

(b) Cooperation between jurisdictions

Because debris flows caused by fill failures can initiate in one jurisdiction (public land agency or private land owner) and create a path of destruction downslope across two or more jurisdictions, it is important to have communication and cooperation among the stakeholders. For example, September 2004 Hurricane Frances triggered road-fill failures on the Blue Ridge Parkway that initiated major debris flows that traveled long distances downslope across the National Forests in North Carolina. The Parkway is managed by the National Park Service (NPS)—Department of Interior; the National Forests are managed by the Forest Service (USFS)—US Department of Agriculture; major engineering on the Parkway is conducted by the Federal Highway Administration (FHA)—US Department of Transportation. Under the auspices of the US Geological Survey Appalachians initiative, the Extreme Storm Team interagency working group was formed to help foster communication and cooperation before, during, and after extreme storms in the Appalachians.

In a 2005 posthurricane investigation of the source (BRP fill failures) of the debris flows on the Grandfather Ranger District of the Pisgah National Forest, the author noticed several other sections of the BRP showing signs of incremental failure, including cracks, scarps, previous asphalt patching, or crack sealing. The author asked the NPS if asphalt pavement surveys had been conducted prior to the September 2004 hurricanes. Upon learning the Federal Highway Administration had conducted such a survey using a video system (VisiData), the author proposed a project for the Extreme Storm Team to submit to the USGS for funding. The team developed the project proposal, and the USGS funded the project that included, among other work, (1) examining the VisiData to see if signs of fill instability were visible prior to September 2004 in the BRP fills that collapsed in September 2004, (2) examining the feasibility of using the VisiData to detect and inventory signs of fill instability on the BRP, and (3) site-specific landslide warning and road closure protocol. Initial project results are reported by Sas and Eaton (2006).

This interagency project also includes a field inventory of fills showing signs of instability along parts of the BRP that traverses high on the mountains above the steep slopes of the Grandfather Ranger District. The inventory can help the NPS (1) to prioritize maintenance or repairs on the BRP, and (2) to develop site-specific warning and road closure protocols when the USGS issues landslides warnings associated with storm or hurricane forecasts. If the fills showing signs of instability are further analyzed and the paths of potential debris flows are projected downslope, then National Forest can conduct a risk assessment of infrastructure and natural resources that may be threatened by these potential debris flows. The NPS could use the USFS risk information as one factor in prioritizing maintenance or repairs on the BRP.

(c) Project development

When a proposed project, e.g., a residential development, is evaluated for landslide or slope-stability hazards, the focus is on (1) the stability of proposed cuts and fills and (2) the presence of any landslides on or adjacent to the project site. However, in the case of projects located on mountainsides or at the base of mountains, the evaluation of debris-flow hazards requires assessment of terrain far away from the project site. Potential debris-flow hazards from natural slopes or human-modified slopes may be located hundreds or thousands of meters away in upland terrain with different property owners or legal jurisdictions. While accessibility, vegetation cover, and other factors hamper assessment of natural slopes, the assessment of existing fill slopes in roads, residential developments, etc., is helped by good access, lack of vegetation, and presence of maintenance records. As a result, inspection of these upland fill slopes provides an excellent opportunity to detect potential debris-flow hazards and to use the information in the siting and design of the project. In some cases, mitigation of the hazard may involve not only siting/design changes in the project area but also remediation of the unstable fill slope in hazard-source area.

Conclusion

Worldwide, the debris-flow hazards associated with fill slopes are increasing due to increasing construction on hill slopes and mountains. This paper provides a framework for site-specific assessments of debris-flow hazards and risks associated with failure of fill slopes. The first step is early detection by conducting an inventory of fills showing signs of incipient or incremental failure: subsidence, tension cracks, scarps, and slumps. When these warning signs indicate a specific fill is hazardous, the second step is a risk assessment, including mapping the path of the potential debris flow from a total fill failure. A proactive loss-prevention program is described, including prioritized maintenance, prioritized repairs, monitoring, warnings for public officials and the public, and risk avoidance or reduction in land-use planning and zoning, cooperation between jurisdictions, and project development.

Many debris-flow hazards on natural slopes in remote, difficult-to-access mountains can only be mitigated by risk-reduction efforts such as land-use planning and zoning. In contrast, the debris-flows hazards on fill slopes in accessible locations can be mitigated by both hazard reduction and risk reduction. Early detection of incremental failure on fill slopes offers real, practical opportunities to prevent debris-flow catastrophes. As a result, it is suggested that agencies devote more attention and resources to early detection, warning, and loss prevention of debris-flow hazards associated with failure of fill slopes.

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