Assessment of Landslide Hazards Resulting from the February 13, 2001, El Salvador Earthquake

A report to the Government of El Salvador and
the U.S. Agency for International Development

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ABSTRACT

On February 13, 2001, a magnitude 6.5 earthquake occurred about 40 km east-southeast of the capital city of San Salvador in central El Salvador and triggered thousands of landslides in the area east of Lago de Ilopango. The landslides are concentrated in a 2,500-km^2 area and are particularly abundant in areas underlain by thick deposits of poorly consolidated, late Pleistocene and Holocene Tierra Blanca rhyolitic tephras that were erupted from Ilopango caldera. Drainages in the tephra deposits are deeply incised, and steep valley walls failed during the strong shaking. Many drainages are clogged with landslide debris that locally buries the adjacent valley floor. The fine grain-size of the tephra facilitates its easy mobilization by rainfall runoff. The potential for remobilizing the landslide debris as debris flows and in floods is significant as this sediment is transported through the drainage systems during the upcoming rainy season.

In addition to thousands of shallow failures, two very large landslides occurred that blocked the Río El Desagüe and the Río Jiboa. The Río El Desagüe landslide has an estimated volume of 1.5 million m^3, and the Río Jiboa landslide has an estimated volume of 12 million m^3. Field studies indicate that catastrophic draining of the Río El Desagüe landslide-dammed lake would pose a minimal flooding hazard, whereas catastrophic draining of the Río Jiboa lake would pose a serious hazard and warrants immediate action. Construction of a spillway across part of the dam could moderate the impact of catastrophic lake draining and the associated flood.

Two major slope failures on the northern side of Volcán San Vicente occurred in the upper reaches of Quebrada Del Muerto and the Quebrada El Blanco. The landslide debris in the Quebrada Del Muerto consists dominantly of blocks of well-lithified andesite, whereas the debris in the Quebrada El Blanco consists of poorly consolidated pyroclastic sediment. The large blocks of lithified rock in Quebrada Del Muerto are unlikely to be remobilized during the rainy season; whereas, the sandy and silty landslide debris in the channel of Quebrada El Blanco is susceptible to remobilization as debris flows that could extend into populated areas on the lower slopes of the volcano.

Around the northern and eastern shore of Lago de Ilopango, earthquake-induced liquefaction and lateral-spreading landslides caused local damage to homes and other structures; this damage was most prevalent in the village of San Agustín. San Agustín is also potentially threatened by floods because it is located on the alluvial fan of the Quebrada El Chaguite drainage basin, which contains hundreds of landslides that have choked numerous small channels with volcanic tephra. As the easily eroded tephra is transported down the drainage system and deposited on the alluvial fan, it could clog the currently active channel with sediment, divert the stream into a new channel, and possibly direct flow through San Agustín, causing more damage and destruction.

INTRODUCTION

On February 13, 2001, a moment magnitude (M_w) 6.5 earthquake occurred about 40 km east-southeast of San Salvador, El Salvador, in the area east of Lago de Ilopango. The earthquake triggered thousands of landslides that are concentrated in an area of about 2,500 km^2 near the earthquake epicenter (figs. 1 and 2). The epicentral area is underlain by thick deposits of late Pleistocene and Holocene rhyolitic tephra and pyroclastic deposits erupted from the Ilopango caldera. The earthquake shaking triggered thousands of falls and slides in the steep-sided valleys that are incised into the tephra deposits. Most of the failures are shallow (<10 m thick) and less than 1000 m^3 in volume, but they are so highly concentrated and locally abundant that they coalesce into nearly continuous failures along many canyon walls (fig. 3).

The February 13 earthquake was the second major damaging earthquake to strike El Salvador in 1 month. On January 13, 2001, a moment magnitude (M_w) 7.6 earthquake occurred at a depth of about 39 km, approximately 60 km off the coast south of the city of Usulután. This major earthquake cause widespread damage throughout the country, 844 fatalities, 4,723 injuries, and triggered a major landslide in the Las Colinas neighborhood of the city of Santa Tecla, a western suburb of San Salvador. The Las Colinas landslide caused approximately 500 fatalities as it slid off the north slope of Balsamo Ridge and into the Las Colinas neighborhood. The January 13 earthquake also caused numerous landslides throughout the Cordillera Balsamo, which is the highland region located south and southwest of San Salvador. Thus, El Salvador was still recovering from the January event when the February 13 earthquake struck.

Figure 1. Map of El Salvador showing the approximate area (red rectangle) of abundant landslides associated with the February 13, 2001, M_w 6.5 earthquake. Most of the landslides were in areas underlain by thick deposits of young rhyolitic tephra erupted from Ilopango caldera, which is now filled by Lago de Ilopango. See figure 2 for detailed map of the area.

The effects and damage from the February 13 earthquake were more localized than the January event, but they were equally devastating. Three hundred fifteen fatalities and 3,399 injuries are attributed to the February event. The localized impacts of the February earthquake were related to its relatively shallow depth, only about 14 km deep. This resulted strong shaking in the immediate area of the earthquake, but the intensity of the shaking diminished rapidly with increas-

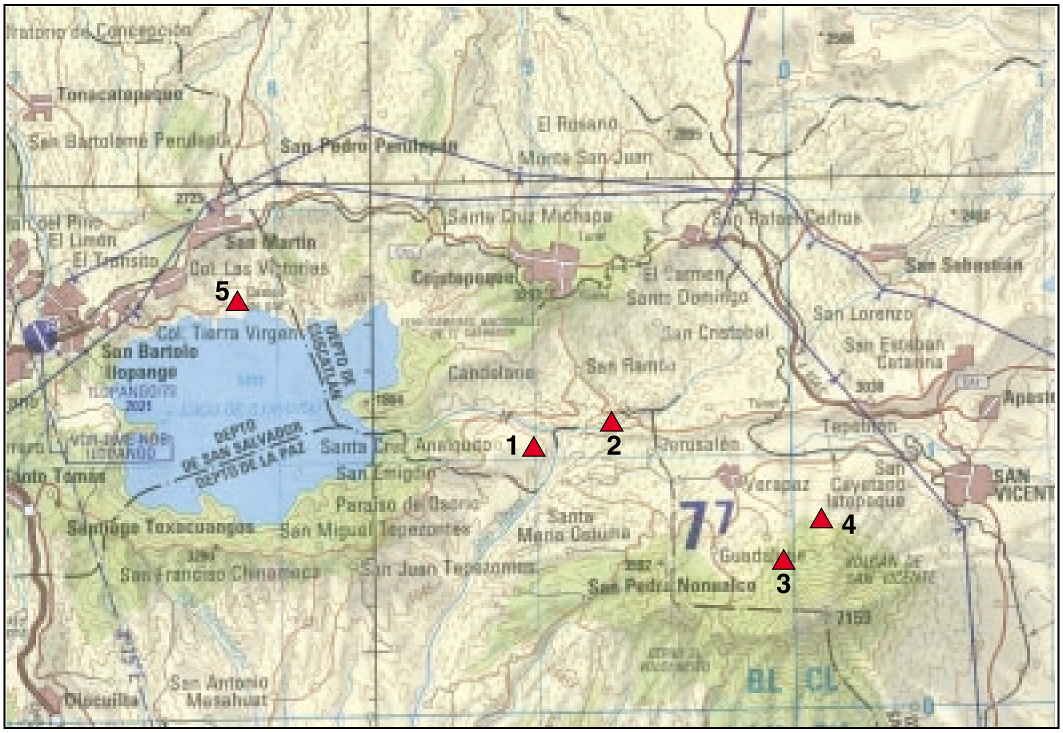

Figure 2. *Detailed map showing the area of abundant landslides associated with the February 13, 2001 earthquake (shown as red rectangle in fig. 1). Numbered triangles refer to sites discussed in text:*

1) Río El Desagüe land slide,
2) Río Jiboa landslide,
3) Quebrada Del Muerto rock slide,
4) Quebrada El Blanco debris slides, and
5) San Agustín-Quebrada El Chaguite area.

Figure 3. *Aerial view of coalescing falls and slides in rhyolitic tephra east of Lago de Ilopango caused by the February 13 earthquake. The abundant fine-grained landslide debris in the valleys may be mobilized as debris flows during the upcoming rainy season.*

ing distance away from the epicenter. The shaking generated thousands of shallow landslides in the deeply dissected terrain surrounding and east of Lago de Ilopango, it triggered large landslides in the Río El Desagüe and the Río Jiboa drainages, and it caused several major landslides on the north side of Volcán San Vicente. It also generated local liquefaction and lateral-spreading landslides in water-saturated, young (Holocene) sediment along the shores of Lago de Ilopango.

Because the landslides are so locally abundant, many valleys of the small-order drainages are clogged with landslide debris that, in many places, has completely buried valley floors. During the upcoming rainy season, this loose landslide debris will be reworked and possibly remobilizing as debris flows. Also landslide-dammed lakes could impound small lakes in the narrow valleys, and failure of these dams could generate moderate to small floods.

The earthquake generated two very large landslides that blocked the Río El Desagüe and the Río Jiboa, creating landslide-dammed lakes (fig. 2). At the time of the earthquake, the flow into these lakes was small because the earthquake occurred in the "dry" season; in the subsequent rainy season, which typically begins in May, the runoff supplying water to these lakes will increase substantially. The landslide dam across the Río El Desagüe has been partially breached by the construction of a small spillway, which controls the size and depth of the lake. Increased streamflow will not significantly increase the size or volume of this lake. However, the lake behind the landslide dam on the Río Jiboa continues to fill and will develop into a very large lake before it finally overtops the landslide. In mid-March 2001, the lake's volume was only about 5 percent of its maximum potential volume of about 7 million m^3.

The earthquake also triggered several significant landslides on the northern slopes of Volcán San Vicente. Prominent slides include a large rock slide in the upper part of the Quebrada Del Muerto and numerous failures along the steep valley walls in the upper part of the Quebrada El Blanco drainage (fig. 2). The large rock slide in the Quebrada Del Muerto is located above the village of Guadalupe and raised concern about the threat it posed to the town. On the north and northeast flank of the volcano, debris slides occurred in several deeply incised gullies. Of these debris slides, the coalescing slides in the Quebrada El Blanco drainage was of greatest concern because of the possibility that debris flows could threaten the town of Tepetitán. This concern is justified because, in 1934, a debris flow partially destroyed the town and caused four deaths. Part of the town was subsequently moved, but much of the area inundated in 1934 has been resettled.

Earthquake-induced liquefaction and lateral-spreading landslides caused localized damage in small settlements around the northeastern shore of Lago de Ilopango. Some settlements along the lake shore face potential flooding and debris flows as large volumes of landslide debris are transported downslope through the area's drainage systems. Some settlements could be threatened by small floods resulting from the catastrophic draining of small lakes that may develop in narrow valleys incised in the thick Tierra Blanca tephra. The village most at risk from these hazards is San Agustín, which is located on an alluvial-fan delta in the north-northeastern part of Lago de Ilopango (fig. 2).

This report summarizes our field observations of the most prominent slope failures associated with the February 13 earthquake. At the request of Salvadoran officials, we offer possible options to help mitigate the impacts of hazardous situations. We conducted our field studies between March 13-21, 2001, about one month after the February earthquake. We acknowledge the assistance and support of the U.S. Agency for International Development (USAID), and the El Salvadoran Ministro de Medio Ambiente y Recurcos Naturales without whose cooperation we would not have been able to respond to this situation in such a timely manner.

RÍO EL DESAGÜE LANDSLIDE

The Río El Desagüe drains eastward out of Lago de Ilopango and is a tributary to the Río Jiboa. Approximately 6.5 km east of the outlet of Lago de Ilopongo, the Río El Desagüe is dammed by a rotational slump/rock avalanche that has an estimated volume of about 1.5 million m^3 (fig. 2). The landslide originated on the south wall of the valley (fig. 4) and is located about 100 m upvalley from the confluence of the Río El Desagüe and the Río Jiboa. Andesitic breccia of the Balsamo Formation compose about 70 percent of the landslide; rhyolitic pyroclastic deposits of the Cuscatlán Formation compose the remainder. The andesite breccia contains clasts ranging in size from coarse sand to boulders of indurated rock that are as much as 3 m in diameter. The landslide has dammed the river, and streamflow in the river has been impounded to form new lake.

Figure 4. *View to the north of the rotational slump/rock avalanche deposit that has dammed the Río El Desagüe near its confluence with the Rio Jiboa. A shallow lake upstream from the landslide (left side of photograph) is draining through a man-made spillway that has been excavated across the toe of the landslide.*

Stream flow in the Río El Desagüe is derived mainly from overflow in Lago de Ilopango. Despite the large size of Lago de Ilopango, the amount of water that drains down the Río El Desagüe is modest. Streamflow records indicate that the annual average discharge in the Río El Desagüe ranges from 0.01 m^3/sec to 0.53 m^3/sec based on records from 1961 to 1973 (División de Meteorológico e Hidrológico, 2001). The maximum peak discharge reported during the recording period was 7.48 m^3/sec in September 1963.

The Río El Desagüe lake is about 1.5 km long and contains an estimated 500,000 m^3 of water. The lake's maximum depth is estimated to be about 5 m on the basis of exposed tree tops near the landslide dam (fig. 4). A hand-dug spillway channel has been excavated across the toe of the landslide to allow the lake to drain. The flow in this 3-m-wide, 2-m-deep channel was about 0.2 m^3/sec in mid-March 2001 and was not eroding landslide debris in the spillway. Large, indurated clasts in the landslide debris have effectively armored the spillway and are preventing erosion of the dam under present low-flow conditions. Because the lake is actively draining across the spillway, its depth and volume will remain relatively constant. Even as flow in the Río El Desagüe increases during the rainy season, the large blocks of lithified rock will minimize erosion of the spillway, and will likely prevent a catastrophic failure of the landslide dam.

The most significant event that is likely to affect the Río El Desagüe lake would be the flood resulting from the failure of the large landslide dam on the Río Jiboa (see the following section for details). A flood caused by failure of the Río Jiboa landslide dam would flow up the Río El Desagüe because of the T-shaped configuration of the Río El Desagüe-Río Jiboa confluence (fig. 2). The flood would flow across the landslide dam and could have sufficient power to significantly erode the landslide dam, which could release the water in the Río El Desagüe lake. How-ever, the volume of water in the Río El Desagüe lake is very small compared to the volume of water that could potentially be released by a catastrophic failure of the Río Jiboa landslide dam. Water in the Río El Desagüe lake would make a negligible contribution to a Río Jiboa flood, therefore no further mitigation measures are needed for the Río El Desagüe landslide dam other than the current spillway.

RÍO JIBOA LANDSLIDE

Approximately 2 km upstream from the confluence of the Río El Desagüe and Río Jiboa, a block slide containing about 12 million m^3 of material completely blocks the Río Jiboa drainage (figs. 2 and 5). The Río Jiboa landslide dam consists primarily of rhyolitic tephra and pyroclastic debris of the Cuscatlán Formation, and most of the landslide material is poorly compacted and extremely porous. The landslide dam is about 700 m long (parallel to the river drainage) and about 250 m wide (across the valley). A lake has formed on the upstream side of the dam; as of March 15, 2001, the lake was about 25 m deep, 400 m long, and was filling at a rate of less than 0.1 m^3/sec (<8600 m^3/day).

If allowed to fill completely, the lake will have an estimated maximum depth of 60 m, a length of about 2 km, and a volume of about 7 million m^3. Two possible breach points exist on the landslide dam (fig. 5); the northern breach point has an estimated elevation of about

Figure 5. *View to the southwest showing the landslide dam on the Río Jiboa. The impounded lake behind the landslide is visible on the lower left. Two possible points are labeled where the reservoir may overtop the landslide dam, if allowed to breach naturally.*

510 m, and the southern breach point has an estimated elevation of 515 m. As of March 15, 2001, the lake-surface elevation was about 475 m. These elevations were estimated from field measurements made with barometric altimeters and hand-held GPS (global positioning satellite) receivers, which have considerable uncertainty. More accurate measurements of the breach-point elevations are needed to better quantify the volume of water that could be retained in the lake.

On the basis of our estimates of the potential maximum lake volume and stream-gauge records of average flow rates for the Río Jiboa, we project that the lake will likely fill and overtop the dam within the next several months. Assuming a near-normal runoff, the lake could reach its maximum capacity as soon as early to mid-August 2001.

Catastrophic failure of the Río Jiboa dam would generate a potentially devastating flood. On the basis of the case study of a similar-size landslide dam composed of similar materials on the Río Pisque in Ecuador (Asanza and others, 1992), we speculate that the lake could drain in several hours once the dam has been overtopped. Upon failure, the flood could reach its peak discharge in a few hours, and the maximum discharge could range from 1,000 to 10,000 m^3/sec, based on a numerical analysis of predicted peak discharges from dam failures (Walder and O'Connor, 1997). This estimated flood is 1.5 to 15 times the maximum discharge recorded on the Río Jiboa at the Montecristo gauging station, the farthest downstream gauging station on the river (División de Meteorológico e Hidrológico, 2001)[6].

If the lake breaches naturally, the landslide dam would erode rapidly because it is composed primarily of unconsolidated volcanic tephra. During the breach, the channel could incise at a rate of several meters to more than 10 m per hour. Such rapid erosion would release huge volumes of water from the lake and cause downstream flooding that could threaten people and property in the lower parts of the Río Jiboa valley.

Such a flood on the Río Jiboa would flow violently down the narrow valley below the landslide dam to the confluence with the Río El Desagüe, which is located only 2 km downstream from the dam. At the confluence, some flood water would flow westward up the Río El Desagüe toward the outlet of Lago de Ilopongo; the remainder would turn southward and flow down the Río Jiboa. The Río Jiboa floodwater that surges up the Río El Desagüe would likely overtop and erode part of the Río El Desagüe landslide dam. This erosion would release some of the water in the Río El Desagüe lake, but the volume of water contributed from this lake would be relatively small compared to the volume released from the Río Jiboa (500,000 m^3 in the Río El Desagüe versus about 7 million m^3 in the Río Jiboa). As the westward momentum of the Río Jiboa flood dissipates, the water will reverse its flow and drain back down the Río El Desagüe and the Río Jiboa. Eventually, all of the water will flow southward toward the coast.

[6] Streamflow records in the Rio Jiboa drainage show that the largest peak discharge observed between 1961 and 1996 was 642 m^3/sec, which was recorded in October 1967 at the Montecristo gauging station.

Effects of Flooding Downstream

The precise impact of a catastrophic flood on the lower reaches of the Río Jiboa are difficult to accurately assess even if a detailed flood-modeling study was conducted. One-dimensional or two-dimensional hydraulic models, which require accurate cross-sectional surveys along the entire study reach, would be limited by the uncertainty in the timing and magnitude of the flood peak, and the unknown effects on the flood hydrograph of the water that had flowed up the Río El Desagüe and then back down the Río Jiboa.

Graphical records from three Río Jiboa gauging stations show the travel time of natural flood peaks through the parts of the valley below the landslide dam. The periods of record for these stations vary between 1961 and 1996. The most upstream gauge, Río Jiboa at San Ramon, was situated at the site of the Río Jiboa landslide, and the most downstream gauge, Río Jiboa at Montecristo, was situated about 20 km downstream from the landslide. The three flood peaks (all less than 200 m^3/sec) that occurred during the common period of operation for these gauges (1972-80) traveled the 20 km from the landslide dam to the Montecristo gauge in 2-4 hours. Because this section of the Río Jiboa is incised into a bedrock canyon, the hydrograph of the flood shows little attenuation between the San Ramon and the Montecristo gauges.

Directly downstream from the Montecristo gauging site, the Río Jiboa valley abruptly widens, and the river flows onto the broad coastal plain. In the confined, narrow bedrock valley, a flood will retain much of its velocity, energy, and erosive power, but in the valley's broad lower reaches, a flood will spread across the coastal plain, dissipating its energy but inundating large areas of the flood plain. A catastrophic flood of 1,000 to 10,000 m^3/sec could inundate most of the river's flood plain and would travel downstream faster than the smaller, natural floods. Such a flood in the lower Río Jiboa valley may cause erosion and scour the abutments of the Highway CA-2 bridge, but it will probably pass beneath this bridge. Such a flood may also partially inundate the eastern portion of the international airport at Comalapa, part of which lies adjacent to the Rio Jiboa floodplain, but the potential inundation area is difficult to determine in the low-relief coastal plain.

The inundation area of a flood is strongly influenced by the topography of the terrain across which the flood flows. Present one-dimensional hydraulic flood-routing models do not adequately forecast inundation areas on broad flood plains. Two-dimensional hydraulic flood models are better suited for such analyses, but they require finely detailed topographic data to constrain the modeling results. Such detailed topographic data are not readily available from present topographic maps of the broad, low-relief floodplain of the lower Rio Jiboa, so developing these two-dimensional models is not possible at the present time.

Possible Mitigation Options

As stated previously, a natural breach from the Río Jiboa landslide dam could quickly release nearly 7 million m^3 of water. A flood generated by such a water release will flow violently through the narrow bedrock portions of the valley at high velocity, allowing little time to warn and evacuate downstream inhabitants. Downvalley in the broader floodplain, the effects of the flood are more difficult to estimate, but it will likely have detrimental effects. To minimize the impact of this flooding, a spillway could be excavated through the landslide debris that would reduce the volume in the impounded lake and reduce the size and effects of the potential flood. A spillway may also provide better control on the timing of the water release.

Our field investigations indicate two logical breach points, one along the northern margin and one along the southern margin of the landslide (fig. 5). The south breach point is located directly below the headscarp of the landslide, and the north breach point is at the north edge of the landslide mass where it reaches the roadway between San Ramon and Verapaz. Of these two points, the north point is the most advantageous site to excavate a spillway for several reasons:

- The north breach point coincides with an existing roadway, providing relatively easy access for heavy equipment to construct a spillway.
- A spillway on the northern side requires less excavation. A spillway on the north would need to be approximately 50-60 m long versus about 700 m long on the south side.
- The northern margin is a safer work site for excavation. The south margin is directly beneath the steep (about 70°), 200-m-high headscarp of the landslide where rock falls are occurring continuously. Rockfall from this escarpment would be a constant hazard to workers. No such hazard exists at the northern margin.
- At the northern margin, there are actually two breach points, an upstream (eastern) point adjacent to the roadway and a second, downstream point several hundred meters to the west. When the lake overtops the upstream breach point, the flood waters will initially flow into and inundate a large tributary valley (Quebrada Seca) of the Río Jiboa, but the downstream breach point will prevent these waters from immediately flowing down the main Río Jiboa. This tributary valley will likely fill quickly (perhaps hours to days), but by monitoring this filling, it will be possible to better gauge when the water will cause failure of the downstream breach point and, therefore, when flood waters will flow down the main Río Jiboa channel.

A spillway excavated across the landslide should be as deep as possible given the constraints on time before the lake fills, and the available equipment and resources. The deeper the spillway, the less water will be impounded in the lake. For each meter in depth of the spillway, the amount of water in the lake will be reduced by many tens of thousands of cubic meters or more.

As the lake level approaches the spillway elevation, all residents in the downstream parts of the Río Jiboa and Río El Desagüe drainages should warned and evacuated in advance of a flood. If possible, an effort should be made to stimulate the breach during daylight hours to help cope with unforeseen situations and emergencies and to assure that the peak flood is completed before dark. This may be possible given the experience from past case studies in similar situations (Asanza and others, 1992). Finally, the landslide dam should be monitored regularly throughout the rainy season to constantly assess any significant changes in the dam's stability.

The preceding discussion focuses on possible mitigation measures related to failure of the dam by overtopping. A more difficult problem is to determine the possibility of a dam failure induced by piping, in which water from the lake percolates through the dam, causes caving and the formation of conduits in the dam through which the lake water can drain. As the depth of the reservoir increases, the potential for piping increases because the impounded water exerts increasing pressure on the dam. Thus as the reservoir fills, the dam should be checked regularly for evidence of significant seepage. If seepage develops, then it should be routinely monitored for changes in the rate of seeping water, which could be evidence of increasing piping and decreasing stability of the dam.

VOLCÁN SAN VICENTE LANDSLIDES

Landslides triggered by the M_w 6.5 earthquake occurred in several deeply incised gullies on the northern flank of Volcán San Vicente. On the volcano's northwestern flank, a large rock slide occurred in the upper part of the Quebrada Del Muerto drainage (fig. 2). To the east and lower on the volcano's slopes, extensive failures occurred along steep valley walls of three gullies that are deeply incised into coarse unconsolidated deposits. These valley-wall failures coalesced into debris slides that filled channel bottoms with loose deposits. Our field investigations in this area focused on the hazard posed by remobilizing this loose debris as debris flows during the rainy season. Of these three eastern gullies, the most likely to pose a hazard is the Quebrada El Blanco because the town of Tepetitán is located on the alluvial fan of this drainage.

Quebrada Del Muerto Rock Slide

The Quebrada Del Muerto rock slide has an estimated volume of about 200,000 m^3 and is composed mainly of large blocks of lithified andesite. The landslide is located high on the northwest flank of Volcán San Vicente at the head of Quebrada Del Muerto. The channel of Quebrada Del Muerto is located directly east of the village of Guadalupe, and because this drainage is so close to the village, there is concern that the rock slide might remobilize as debris flows and endanger the village.

Debris within the rock slide ranges in size from sand to large boulders (fig. 6), but the landslide debris is dominantly large boulders, some as much as several meters in

diameter. Owing to the large size and indurated character of the rock fragments, it is unlikely that this landslide debris will be remobilized by rainfall into debris flows that will threaten downstream settlements or structures. Some of the finer-grained debris (sand and gravel fraction) could be transported downstream, but most of the rainfall and surface-water runoff will infiltrate the landslide debris and cut small runoff channels across the surface. Little of this coarse debris will be mobilized by flowing water. Therefore, it is unlikely that the town of Guadalupe will be seriously threatened by debris flows remobilized from this slide material unless a new large failure is triggered from the same source area by abnormally heavy rainfall.

Figure 6. *View toward the source of the Quebrada Del Muerto rock slide on the northwest flank of Volcán San Vicente. The rockslide is composed mainly of well-indurated andesite, which has broken into boulder-sized debris. The composition and size of fragments in the landslide debris make it unlikely that the material will be remobilized as debris flows during the upcoming rainy season.*

Quebrada El Blanco Debris Slides

Lower, on the northern slope of Volcán San Vicente, numerous coalescing debris slides were triggered by the earthquake along the 40- to 50-m-deep incised gully of the Quebrada El Blanco. Unconsolidated pyroclastic and debris-flow deposits in the steep valley walls failed during the earthquake and produced numerous debris slides that are typically 1-3 m thick and have a cumulative volume of approximately 250,000 m^3 (fig. 7).

Debris from these landslides has clogged the channel bottom with sandy and silty sediment that may remobilize as debris flows during the rainy season. Large flows triggered in Quebrada El Blanco may extend down to the broad, shallow slopes of the quebrada's alluvial fan. The small town of Tepetitán is located on part of this alluvial fan. About 1 km upslope from Tepetitán, drainage in Quebrada El Blanco is confined to a channel that is incised several meters into older alluvial deposits. However, closer to the town, the drainage emerges onto a broad open slope that is cut by shallow channels less than 2 m deep. This broad open slope is the depositional surface of previous debris flows, and the active channels of the fan have routed flows near and toward Tepetitán in the recent past. The last debris flow that reached the town occurred in 1934, caused several fatalities, and buried parts of the old village in about 60 cm of sediment. After the 1934 event, most of the town was relocated to a higher, safer site, but

Figure 7. *View to the northwest down the upper reaches of Quebrada El Blanco channel showing coalescing debris slides from the valley walls. The channel bottom is clogged with landslide debris, and rainfall runoff may trigger debris flows in these sandy, silty deposits.*

over the years, the original site has been resettled.

The shallow nature of the channels and the flat character of the topography near Tepetitán make it difficult to determine the precise direction that debris flows will take if they occur and emerge from the more deeply incised channel upstream. Shallow channels near Tepetitán could get clogged with debris and divert flows westward, away from the town, or northeastward toward the town. The channels could also remain open and guide the flows toward the town. Preliminary debris-flow simulation models (J.J. Major, U.S. Geological Survey, unpublished data) suggest that debris flows having volumes in excess of 100,000 m^3 that remain in the shallow channels could potentially reach the town.

Recommendations for Mitigation

The most effective mitigation measure for debris-flow hazards in the town of Tepetitán is to construct a sediment check dam or diversion levee(s), which will redirect small- to moderate-volume flows. Such structures are used successfully in debris-flow prone areas of the U.S., such as California, where the sediment basins are designed to collect the maximum volume of sediment expected from a specific drainage. As these basins are filled, the accumulated debris is removed to assure that the basin can retain future flows. Such basins must be designed to allow water from the flows to pass while retaining the captured sediment.

Diversion levees are also effective devices to mitigate debris-flow hazards by diverting flows around and away from inhabited sites and man-made structures. Such levees are feasible where ample space is available to deposit the rerouted debris and where no people or property are at risk in the depositional areas. If either of the above mitigation options is considered, then hydraulic engineers should be engaged to design effective sediment catch basins or diversion levees.

SAN AGUSTÍN DELTA AND EL CHAGUITE DRAINAGE BASIN

The village of San Agustín is located on the northeastern shore of Lago de Ilopango, approximately 5.5 km southeast of San Martín (fig. 2). The village is situated on the active alluvial fan of Quebrada El Chaguite. The Quebrada El Chaguite drains an approximately 10 km^2 area of deeply dissected terrain between the San Agustín and the northern edge of the Lago de Ilopango caldera rim (fig. 8). During the February 13 earthquake, many homes in the village were severely damaged or destroyed by strong shaking and/or liquefaction and lateral spreading caused by the earthquake. The liquefaction and lateral spreads locally formed fissures and small scarps in the parts of the village adjacent to the lake shore. The recently constructed school in San Agustín suffered virtually no damage because of the quality of the construction and because it is located on a relatively stable, elevated site above the young alluvial fan. The school's sturdy construction allowed it to endure the strong shaking, and it's location above the young alluvial fan avoided damage from liquefaction and lateral spreading.

The February 13 earthquake caused hundreds of small landslides throughout the Quebrada El Chaguite drainage basin. Many valleys in the drainage basin are filled with loose tephra that will impede runoff during the rainy season and that could locally form small landslide-dammed lakes. Catastrophic breaching of these lakes could quickly release water that could produce small to moderate floods in San Agustín. Furthermore, the massive quantities of easily eroded tephra in the valleys will be readily transported downvalley and will likely cause significant changes in the hydrodynamics of the Quebrada

El Chaguite. The abnormally large quantity of sediment being carried by the quebrada could clog the current stream channel with sediment, divert the flow of water across the alluvial fan, and possibly flood parts of San Agustín (fig. 8).

Direct Effects of the Earthquake in San Agustín

Two effects of the February 13 earthquake caused widespread damage in San Agustín: earthquake-induced strong shaking, and ground failures caused by liquefaction and lateral spreading. Damage from strong shaking had the greatest impact on poorly constructed buildings, particularly those built with adobe bricks. Liquefaction caused damage where the ground surface beneath buildings spread laterally.

Liquefaction and lateral spreading are common phenomena that occur during strong earthquakes. They usually occur in young, water-saturated sediment; much of San Agustín is built on deposits that have these characteristics. During the strong, sustained shaking associated with damaging earthquakes, water in the pores between the sediment grains is pressurized as the seismic waves travel through the deposits. The pressurized water reduces the strength of the sediment by pushing the sediment grains apart. As a result, the sediment can temporarily behave more like a fluid than a solid. In this fluid-like state, the sediment can flow laterally down very gentle slopes (gradients of only a few degrees) to form lateral-spreading landslides. At the upper end of lateral-spreading landslides, scarps

Figure 8. *View to the north of the Quebrada El Chaguite drainage basin and the village of San Agustín (in left foreground). The February 13 earthquake caused extensive damage in the village and widespread landslides throughout the drainage basin. The village of San Agustín is located adjacent to the active channel of the young alluvial fan of the quebrada.*

Figure 9. *Ground deformation and scarps that formed at the head of a lateral-spreading landslide adjacent to the "Zona Experimental de Culturo de Peces" on the eastern shore of Lago de Ilopango. Buildings that span scarps similar to these commonly suffer considerable damage.*

can form (fig. 9), and structures that span these scarps are likely to be damaged. In addition, the pressurized water mixed with sand commonly erupts onto the ground surface along fissures and cracks and leaves distinctive deposits of sand called sand boils (fig. 10).

Generally, buildings constructed of adobe bricks suffered significant damage from the strong shaking, whereas buildings constructed of reinforced cinder blocks suffered limited damage. The adobe buildings had little or no internal reinforcement, and when the shaking dislodged a few bricks, entire walls became unstable and collapsed. In contrast, cinder-block buildings usually contained some reinforcement with steel rebar, and the more reinforcement a structure contained, the less damage it suffered. However, some cinder block buildings were damaged because they straddled scarps that formed as a result of lateral spreading (fig. 11).

In the absence of any future strong nearby earthquakes (approximately magnitude 5.5 or greater), it is unlikely that additional liquefaction will occur or that the lateral spreading will be reactivated. However, the San Agustín area is in a seismically active part of El Salvador, so it is possible that strong earthquakes could occur in the region, certainly on decade-long time scales. It is difficult to accurately determine exactly where lateral-spreading landslides may form during future earthquakes other than to note that they are more likely to occur where 1) the water table is close to the surface and 2) at sites where liquefaction has occurred in the past. Because the water level in Lago de Ilopango is a major control on the local depth of the water table, sites close to the shore line are more prone to liquefaction and lateral spreading than sites more distant from the lake or at higher elevations.

Figure 10. *Liquefied sand that flowed to the surface through cracks and fissures during the February 13 earthquake in San Agustín. These sand boils formed on the village's soccer field.*

Figure 11. *Damage to a home in San Agustín from lateral spreading beneath the structure. Further movement probably not occur again unless the sediment is severely shaken by another strong earthquake.*

Potential Flood Hazards following the Earthquake

The Quebrada El Chaguite drainage basin, which includes the tributary drainages of the Quebrada El Camalote and the Quebrada Guluchapa, contains deposits of poorly consolidated Tierra Blanca tephra that are locally tens of meters thick (fig. 12). The February 13 earthquake caused hundreds of landslides in the drainage basin. Many steep canyon walls collapsed and filled the adjacent valleys with large amounts of loose, soft debris (fig. 12).

The coming rainy season will mobilize a great deal of the sediment in the drainages above San Agustín, and this mobilized sediment could threaten the village as debris flows and hyperconcentrated flows (sediment-rich floods). In the narrow valleys, much of the sediment will remain entrained in the flows, but when the flows reach the alluvial fan, their capacity to transport sediment will be reduced. As a result, sediment will be deposited in the active channel (fig. 8) and on the floodplain on the alluvial fan. As this sediment load is deposited, the current channel may become filled with sediment, and the stream may divert into an new channel. This diversion could direct the flow into San Agustín and cause widespread flooding and destruction.

Recommendations For Mitigation

San Agustín is exposed to risk from several natural hazards. Liquefaction and lateral spreading caused damage during the February 13 earthquake, but these hazards will not cause further damage unless another strong earthquake occurs. To minimize the potential damage from future lateral spreading, one option is to relocate those homes damaged by lateral spreading to sites farther away from the lake shore or on higher ground, where the potential for lateral spreading is less. A possible relocation site is on the northwestern side of the village, in the area that is currently occupied by families living in emergency shelters. The vacated part of the village where lateral spreading occurred (and may occur in the future) could be used for recreational purposes such as soccer fields, where no structures would be located.

Figure 12. *Widespread landslides in the Quebrada El Camalote, a tributary to the Quebrada El Chaguite drainage basin, exposed thick deposits of Tierra Blanca tephra. The loose tephra has now clogged the narrow valleys, and during the coming rainy season, much of the easily eroded tephra will be transported down the drainage system and into Lago de Ilopango.*

Figure 13. *View toward the north of San Agustín and the adjacent stream course where large sediment influxes in the rainy season may cause the stream to change course and flow toward the village. A proposed diversion levee would direct the flow to the east into an ancient stream channel. This diversion would likely damage a road to a nearby finca (coffee plantation), but would reduce the potential of flooding in the village.*

Flooding during the coming rainy season poses a more imminent threat to San Agustín and could originate in two ways. First, small lakes could form in the sediment-clogged valleys of the Quebrada El Chaguite and tributary drainage basins, and breaching of these lakes could send the impounded water rushing down the valley. Because the valleys in the upper reaches of the drainage basins are so narrow, the volume of water likely to be released in these breaching events would probably be relatively small and probably would not cause substantial flooding. The more significant flood hazard is associated with excessive sedimentation in the current stream channel and diversion of the stream flow into a new channel. If a new channel directed flow into the town, flood damage could be extensive. To prevent this possibility, we recommend that a diversion levee be constructed in the active channel immediately upvalley from San Agustín. This levee should be designed to redirect stream flow to the east, away from the village, and into an abandoned channel on the eastern side of the alluvial fan (fig. 13). The presence of a preexisting channel greatly simplifies the diversion process. Streamflow diverted into this abandoned channel will pass directly into Lago de Ilopango. Flow down this abandoned channel will damage a small road that leads to a nearby finca, but construction of a diversion levee will reduce the flood hazard in the village of San Agustín.

SUMMARY AND CONCLUSIONS

The February 13, 2001, earthquake in central El Salvador triggered thousands of landslides in the area between Lago de Ilopango and the city of San Vicente. In much of this area, strong ground shaking caused extensive failures on steep walls of deeply incised valleys. The area most heavily affected by landslides is underlain by thick deposits of unconsolidated late Pleistocene- and Holocene-age volcanic tephra emplaced during eruptions of Ilopango caldera.

Large landslides blocked two major rivers in the area: the Río El Desagüe and the Río Jiboa. The Río El Desagüe landslide has impounded a modest-size lake (about 500,000 m^3), whereas the lake potentially impounded by the Río Jiboa landslide could contain about 7 million m^3 of water. Water from the Río El Desagüe lake is currently flowing over its landslide dam through a small, man-made spillway. The Río El Desagüe landslide consists largely of blocks of indurated andesitic breccia that armors channels incised into the landslide. These blocks retard the rapid release of large amounts of water from the lake. All of the runoff from the upper Río Jiboa watershed is filling the landslide-dammed lake, which as of March 2001, contained only slightly more than 5 percent of its maximum potential volume. The Río Jiboa landslide consists mostly of easily eroded volcanic tephra and is susceptible to a catastrophic failure when overtopped by water from the lake. The resulting flood, which would likely occur within the next several months (in the absence of intervention measures), would flow violently down the narrow bedrock valley that extends about 20 km below the dam. Farther downstream, the flood would inundate large areas of the broad coastal plain and may potentially flood part of the international airport.

Several large failures occurred on the northern slopes of Volcán San Vicente. A large rock slide occurred in the upper part of Quebrada Del Muerto, above the town of Guadalupe. The rock slide is composed mainly of 1-3 m diameter blocks of lithified andesite. Field studies indicate that this landslide debris in not likely to be remobilized, and therefore does not pose a serious hazard to the town. On the north-northeastern side of the volcano, the Quebrada El Blanco has eroded a deeply incised gully into pyroclastic and debris-flow deposits. Many parts of the steep valley walls failed during the earthquake and filled the adjacent channel with loose debris. This debris will likely be reworked during the rainy season. If it is remobilized as debris flows and the flows are of sufficient size, then they could threaten parts of the small town of Tepetitán, which is located on the alluvial fan of the Quebrada El Blanco.

At several sites along the shores of Lago de Ilopango, the earthquake caused liquefaction and lateral-spreading landslides that locally damages structures, including many buildings in the village of San Agustín.

San Agustín is also exposed to a significant flooding hazard because of its location on the alluvial fan of Quebrada El Chaguite drainage basin. Extensive landslides occurred in the upper reaches of this and tributary drainage basins, and large volumes of loose, easily eroded sediment are available for transport during the rainy season. Redistribution of this sediment on the alluvial fan could divert the stream into a new channel. If this diversion directs flow into the village, then flooding in San Agustín would cause widespread damage and impose additional hardships on the citizens.

The February 13 earthquake was the second disastrous earthquake to strike the small country of El Salvador in one month. Although the effects of this earthquake were restricted to a relatively small area, the impact of the effects were devastating to a country that was already trying to recover from a previous major earthquake. Abundant landslides triggered by the February 13 earthquake filled many drainage channels with easily transported landslide debris that will be reworked and redistributed during the next rainy season, which will start about May 2001. Debris flows and potentially catastrophic floods pose serious threats that could cause additional damage and loss of life if not recognized in advance. However, with advanced awareness and with the implementation of appropriate mitigation measures, the effects of debris flows and floods can be anticipated, and the losses can be reduced and minimized.

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