Summary of Preliminary 2D Inundation Modeling for Three Hattian Landslide Dam Breach Scenarios

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On October 8, 2005, a **M** 7.6 earthquake near Muzafarrabad, Pakistan (Figure 1), triggered a landslide that dammed the Karli River and one of its tributaries about 4 km upstream of the confluence of the Karli and Jhelum rivers near the town of Hattian Bala. The smaller dam on the tributary of the Karli River has been artificially breached and is no longer a hazard. When the larger dammed lake on the Karli River has filled enough to flow over the landslide blockage, it will have impounded about 60 million cubic meters of water. This lake will drain through the landslide dam as it breaches during the spring runoff or during the monsoon season in early summer. The inundation associated with the Karli River landslide dam breach endangers a substantial downstream population, particularly the population located in the vicinity of Hattian Bala at the confluence of the Karli and Jhelum rivers. To help mitigate this hazard, we used an accurate two-dimensional flow model to simulate dambreak flows associated with three breach-rate downcutting scenarios, and estimated inundation depths and peak flow velocities. We superimposed inundation extents and other attributes on photographic images of the region to provide clear delineation of potential impacts on populated areas near the confluence of the Karli and Jhelum rivers.

The numerical simulations are done on a two-dimensional mesh of the topography formed from square cells 5m on a side and derived from a high-resolution post-landslide digital elevation model (DEM). Using pre- and post landslide DEMs, we reconstructed the landslide mass blocking the Karli River, shown in Figure 2. We modified the breach to reflect the artificial cut made to breach the smaller tributary dam, and we cut a 7-m-deep spillway through the lowest elevation portion of the Karli River landslide dam to approximate remediation activities to reduce downstream impacts of the landslide dam breach. It appears that an 18-m-deep spillway may instead be implemented prior to the dam breach, so our simulations would likely overestimate impacts if the 18-m-deep spillway excavation is achieved prior to overtopping of the dam. To initiate flow over the dam, we flooded the region upstream of the Karli River landslide dam to a water surface elevation 0.2 m higher than needed to flow over the top of the landslide dam.

We simulated inundations associated with three dam-breach downcutting rate scenarios as water flows over the top of the dam. The highest breach-rate scenario was used to simulate a potential liquefaction of the blockage and its rapid incorporation into a flow. The two lower breach rate scenarios are associated with stable downcutting of the slide. These three breach scenarios bracket the range of maximum inundation conditions associated with two classes of breach behavior. A breach rate of 1000 m/hr was used to represent maximum inundation associated with rapid liquefaction and integration of the slide mass into the flow over a period of 8 minutes. A breach downcutting rate of 100 m/hr was used to represent the maximum inundation associated with stable downcutting of the slide, consistent with the maximum estimated downcutting rates for landslide dams (Walder and O'Connor, 1997). A lower breach downcutting rate of 50 m/hr was used to illustrate the reduced inundation associated with stable downcutting of the slide, at a rate consistent with the median estimated downcutting rates observed for landslide dams (Walder and O'Connor, 1997).

For all three breach rate scenarios, we used initial conditions of 100 m^3/s baseflow in the Karli River and 2000 m^3/s in the Jhelum River obtained by looking up baseflow conditions on the world wide web. These baseflow conditions, particularly in the Jhelum River, can significantly impact the inundation near the confluence of the Karli and Jhelum Rivers as well as along the Jhelum River both upstream and downstream of its confluence with the Karli River. We assumed these values, and actual flows may be quite variable, particularly during the monsoon season. The method used for calculating the dambreak flow is similar to that described in Denlinger and Iverson, (2001), with the density set to 1 and an average surface roughness of 1.4 meters assumed in place of Coulomb bed friction. For each breach scenario we show three figures for each reach; (1) maximum depth, (2) time to maximum depth, (3) maximum product of depth and velocity to illustrates hazards to people on the ground, based upon experiments done in flumes on the ability of human subjects to stand or move in a flow with a given depth and velocity (Abt et al., 1989), and (4) maximum velocity. An overview of the entire modeled region using flows for the maximum stable downcutting breach rate of 100 m/hr is shown in Figures 3 through 5.

The depths and velocities obtained from the 2D simulations differ substantially from those obtained from the 1D DAMBRK model except at the dam. Both 1D and 2D models provide flow over the dam that approximates flow over a weir. However once the dambreak flow leaves the breached dam, the hydraulics resulting from rugged channel topography reduce the discharge and represented by the 2D simulations. For example, in Figure 6 we show a plot of the discharge versus time over the breach for a downcutting rate of 100 m/hr. The maximum discharge calculated over the breach is nearly 25,000 m^3/s, which is consistent with calculations for flow over a weir and with 1d models such as DAMBRK. However, as reported below, this discharge is four times higher than the maximum discharge achieved a kilometer downstream when channel topography is included in the model. This flow of nearly a million cubic feet per second into the rugged Karli River system forms a series of chutes and pools that reduces the discharge through the river system by 75%. These considerations apply to each scenario, as discussed below.

For the case of liquefaction of the breach (high breach rate of 1000 m/hr), we show maximum depth, time to maximum depth, and the product of depth and velocity for three successive reaches of the river: near the landslide (Figures 7-10), upstream of the junction of the Karli and Jhelum Rivers (Figures 11-14), and downstream of the junction of the Karli and Jhelum Rivers (Figures 15-18). Much of the infrastructure on terraces near the confluence of the Karli and Jhelum rivers are severely impacted and may be removed, including tent cities and refugee camps set up after the **M** 7.6 October 8, 2005 earthquake, since much of the flow exerts enough power to remove buildings. In almost all of the inundated area, humans will be swept along with the flow. The time to maximum inundation at the confluence is 11 minutes, making anticipation of this hazard critical to avoid catastrophic loss of human life.

For the case of maximum downcutting rate in a stable blockage (100 m/hr breach rate), we again show maximum depth, time to maximum depth, and the product of depth and velocity for three successive reaches of the river: near the landslide (Figures 19-22), upstream of the junction of the Karli and Jhelum Rivers (Figures 23-26), and downstream of the junction of the Karli and Jhelum Rivers (Figures 27-30). In contrast to the 1000 m/hr rate, much of the infrastructure on the terraces near the confluence of the Karli and Jhelum rivers is not affected. Because the flow into the Karli from the dam is broken up into a series of chutes and pools, the peak discharge halfway down the Karli River is about 5,700 m^3/s (~202,000 ft^3/s) or about 25% of the peak dambreak flow into the river. At this discharge, both the Karli and Jhelum rivers, modified annually by monsoon conditions, can convey enough water to handle the most of the peak discharge obtained from a downcutting rate of 100 m/hr within the landslide mass. Maximum inundation at the confluence occurs about 30 minutes after downcutting of the blockage begins. Consequently, though there is some impact along both rivers with a 100 m/hr breach rate, the time to evacuate is three times greater than for rapid removal of the blockage, and the potential for loss of human life is much lower.

For the case of the median downcutting rate in a stable blockage (50 m/hr breach rate), we again show maximum depth, time to maximum depth, and the product of depth and velocity for three successive reaches of the river: near the landslide (Figures 31-34), upstream of the junction of the Karli and Jhelum Rivers (Figures 35-38), and downstream of the junction of the Karli and Jhelum Rivers (Figures 39-42). The peak discharge halfway down the Karli River is about 2945 m^3/s (~104,000 ft^3/s). The Karli and Jhelum rivers, modified annually by monsoon conditions, easily convey the peak discharge obtained from a 50 m/hr breach rate of the landslide mass, and produce a flow comparable to those obtained with monsoon rains. Maximum inundation at the confluence occurs 48 minutes after downcutting of the blockage begins. Thus the time to evacuate is greater than for more rapid removal of the blockage, and far fewer areas are impacted with life-threatening flow conditions.

Subject to the assumed baseflow conditions on the Karli and Jhelum rivers, these three breach-rate scenarios bracket the maximum inundation impacts associated with the two failure modes of the Hattian landslide dam, and place strong constraints on inundated areas and the destructive potential of the inundation for Karli River peak discharges between 2945 m^3/s and 31,000 m^3/s. The moderate breach-rate scenario shows that breach-rates of 50 m/hr or less will likely only inundate the lowest terraces adjacent to the Karli and Jhelum rivers. If baseflow conditions on the Jhelum River substantially exceed the assumed baseflow of 2000 m^3/s, maximum inundations along the Jhelum River and the Karli River near the confluence with the Jhelum River will be larger than indicated in this report.

The actual mode of failure of the dam will control the development and extent of the flood hazard, and this placed a high priority on observations of the breach of the smaller landslide dammed lake. It is unfortunate that through difficult communications, observations of the mode of failure and downcutting through the blockage by this smaller lake were not made. Data from the artificial breach of the smaller dam on the tributary of the Karli River could have provided information necessary to constrain the breach rate of the dammed Karli River when it overtopped the blockage, but communication prior to the breach was difficult and uncertain. In the future, monitoring of the breach downcutting rate, the slope failure behavior of the slide mass as it's being breached in terms of sliding and or liquefaction, and final landslide post-breach shape would be useful to refine breach estimates.

References

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Figure 1. Location of the landslide and blockage on the Karli River, Pakistan. The Karli Rivers was blocked by the landslide debris during a **M** 7.6 earthquak on October 8, 2005 that was located near Muzafarrabad, Pakistan.

Figure 2. Detail of the blockage on the landslide topography. A 5m by 5m grid of this topography was used for the flow calculations. Flow over the landslide damming the Karli river (on the left) eroded the blockage to simulate a dambreak flow as described for the three different scenarios in this report.

100 m/hr Breach Rate Overview PDF File Captions for Figures 3-5

Figure 3. Entire modeled region of the landslide dam and Karli and Jhelum Rivers in Pakistan, showing the maximum inundation obtained with a 100 m/hr downcutting (erosion) rate of the landslide debris damming the Karli River.
Figure 4. Entire modeled region of the landslide dam and Karli and Jhelum Rivers in Pakistan, showing the time to maximum inundation obtained with a 100 m/hr (erosion) rate of the landslide debris damming the Karli River.
Figure 5. Entire modeled region of the landslide dam and Karli and Jhelum Rivers in Pakistan, showing the depth*maximum(velocity, 1.0 m/s) obtained with a 100 m/hr downcutting (erosion) rate of the landslide debris damming the Karli River. Most of the inundated area is lethal to human life.

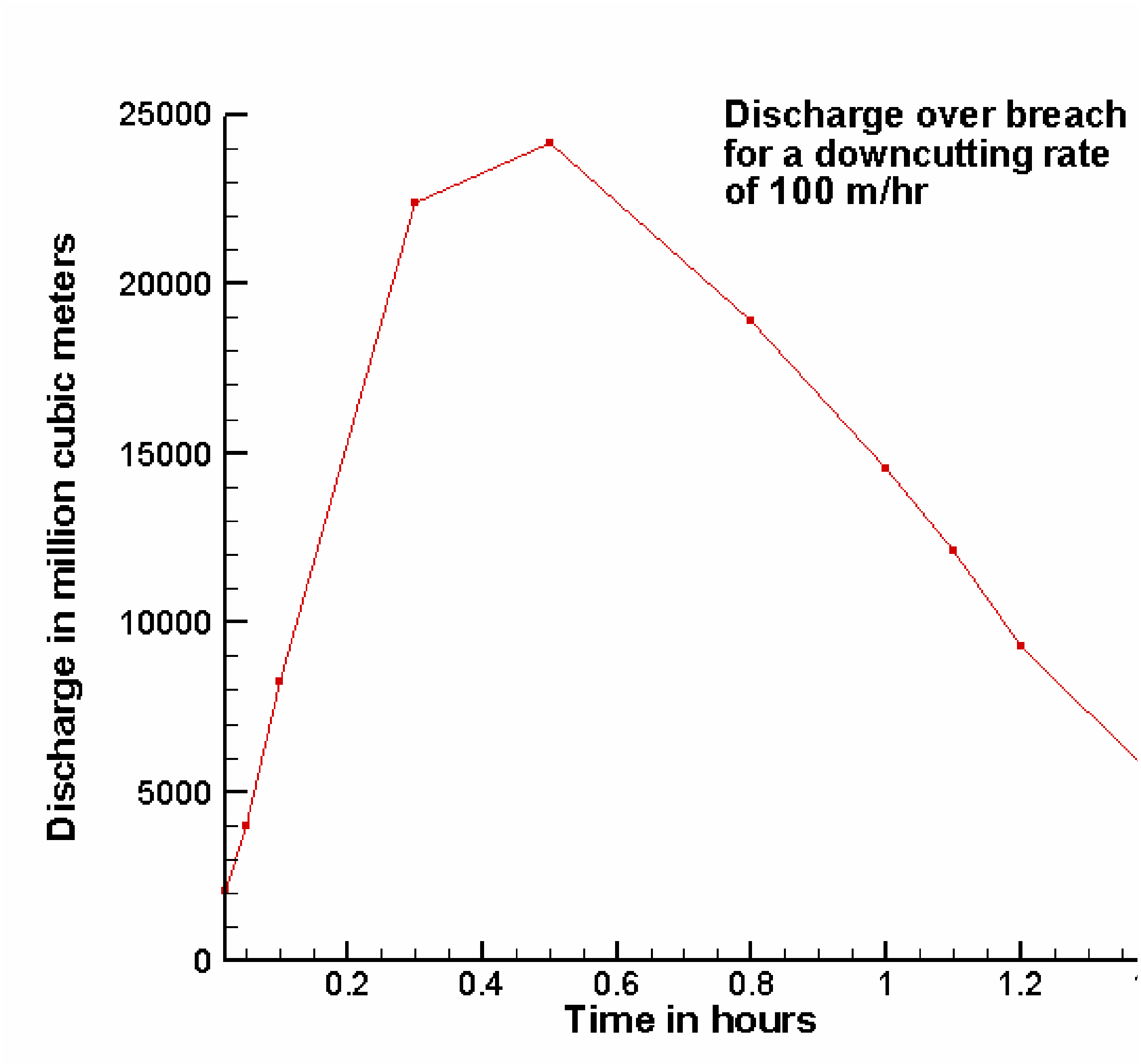

Figure 6. Discharge versus time when the water flowing over the breach cuts down through the landslide dam at a rate of 100 m/hr. The maximum discharge at the breach is comparable to 1d models for flow over a weir, but four times larger than occurs a short distance downstream because of chute and pool development within the three dimensional drainage of the Karli River.

1000 m/hr Breach Rate Overview PDF File Captions for Figures 7-18

Figure 7. Maximum inundation in the upper Karli River drainage near the landslide dam for rapid disintegration of the dam using a 1000 m/hr downcutting rate.
Figure 8. Time to maximum inundation in the upper Karli River drainage near the landslide dam for rapid disintegration of the dam using a 1000 m/hr downcutting rate.
Figure 9. Maximum value of depth*maximum(velocity, 1.0 m/s) in the upper Karli River drainage near the landslide dam for rapid disintegration of the dam using a 1000 m/hr downcutting rate.
Figure 10. Maximum velocity in the upper Karli River drainage near the landslide dam for rapid disintegration of the dam using a 1000 m/hr downcutting rate.
Figure 11. Maximum inundation upstream of the junction of the Karli River with the Jhelum River for rapid disintegration of the landslide dam using a 1000 m/hr downcutting rate.
Figure 12. Time to maximum inundation upstream of the junction of the Karli River with the Jhelum River for rapid disintegration of the landslide dam using a 1000 m/hr downcutting rate.
Figure 13. Maximum value of depth*maximum(velocity, 1.0 m/s) upstream of the junction of the Karli River with the Jhelum River for rapid disintegration of the landslide dam using a 1000 m/hr downcutting rate.
Figure 14. Maximum velocity upstream of the junction of the Karli River with the Jhelum River for rapid disintegration of the landslide dam using a 1000 m/hr downcutting rate.
Figure 15. Maximum inundation downstream of the junction of the Karli River with the Jhelum River for rapid disintegration of the landslide dam using a 1000 m/hr downcutting rate.
Figure 16. Time to maximum inundation downstream of the junction of the Karli River with the Jhelum River for rapid disintegration of the landslide dam using a 1000 m/hr downcutting rate.
Figure 17. Maximum value of depth*maximum(velocity, 1.0 m/s) downstream of the junction of the Karli River with the Jhelum River for rapid disintegration of the landslide dam using a 1000 m/hr downcutting rate.
Figure 18. Maximum velocity downstream of the junction of the Karli River with the Jhelum River for rapid disintegration of the landslide dam using a 1000 m/hr downcutting rate.

100 m/hr Breach Rate Overview PDF File Captions for Figures 19-30

Figure 19. Maximum inundation in the upper Karli River drainage near the landslide dam for rapid disintegration of the dam using a 100 m/hr downcutting rate.
Figure 20. Time to maximum inundation in the upper Karli River drainage near the landslide dam for rapid disintegration of the dam using a 100 m/hr downcutting rate.
Figure 21. Maximum value of depth*maximum(velocity, 1.0 m/s) in the upper Karli River drainage near the landslide dam for rapid disintegration of the dam using a 100 m/hr downcutting rate.
Figure 22. Maximum velocity in the upper Karli River drainage near the landslide dam for rapid disintegration of the dam using a 100 m/hr downcutting rate.
Figure 23. Maximum inundation upstream of the junction of the Karli River with the Jhelum River for rapid disintegration of the landslide dam using a 100 m/hr downcutting rate.
Figure 24. Time to maximum inundation upstream of the junction of the Karli River with the Jhelum River for rapid disintegration of the landslide dam using a 100 m/hr downcutting rate.
Figure 25. Maximum value of depth*maximum(velocity, 1.0 m/s) upstream of the junction of the Karli River with the Jhelum River for rapid disintegration of the landslide dam using a 100 m/hr downcutting rate.
Figure 26. Maximum velocity upstream of the junction of the Karli River with the Jhelum River for rapid disintegration of the landslide dam using a 100 m/hr downcutting rate.
Figure 27. Maximum inundation downstream of the junction of the Karli River with the Jhelum River for rapid disintegration of the landslide dam using a 100 m/hr downcutting rate.
Figure 28. Time to maximum inundation downstream of the junction of the Karli River with the Jhelum River for rapid disintegration of the landslide dam using a 100 m/hr downcutting rate.
Figure 29. Maximum value of depth*maximum(velocity, 1.0 m/s) downstream of the junction of the Karli River with the Jhelum River for rapid disintegration of the landslide dam using a 100 m/hr downcutting rate.
Figure 30. Maximum velocity downstream of the junction of the Karli River with the Jhelum River for rapid disintegration of the landslide dam using a 100 m/hr downcutting rate.

50 m/hr Breach Rate Overview PDF File Captions for Figures 31-42

Figure 31. Maximum inundation in the upper Karli River drainage near the landslide dam for rapid disintegration of the dam using a 50 m/hr downcutting rate.
Figure 32. Time to maximum inundation in the upper Karli River drainage near the landslide dam for rapid disintegration of the dam using a 50 m/hr downcutting rate.
Figure 33. Maximum value of depth*maximum(velocity, 1.0 m/s) in the upper Karli River drainage near the landslide dam for rapid disintegration of the dam using a 50 m/hr downcutting rate.
Figure 34. Maximum velocity in the upper Karli River drainage near the landslide dam for rapid disintegration of the dam using a 50 m/hr downcutting rate.
Figure 35. Maximum inundation upstream of the junction of the Karli River with the Jhelum River for rapid disintegration of the landslide dam using a 50 m/hr downcutting rate.
Figure 36. Time to maximum inundation upstream of the junction of the Karli River with the Jhelum River for rapid disintegration of the landslide dam using a 50 m/hr downcutting rate.
Figure 37. Maximum value of depth*maximum(velocity, 1.0 m/s) upstream of the junction of the Karli River with the Jhelum River for rapid disintegration of the landslide dam using a 50 m/hr downcutting rate.
Figure 38. Maximum velocity upstream of the junction of the Karli River with the Jhelum River for rapid disintegration of the landslide dam using a 50 m/hr downcutting rate.
Figure 39. Maximum inundation downstream of the junction of the Karli River with the Jhelum River for rapid disintegration of the landslide dam using a 50 m/hr downcutting rate.
Figure 40. Time to maximum inundation downstream of the junction of the Karli River with the Jhelum River for rapid disintegration of the landslide dam using a 50 m/hr downcutting rate.
Figure 41. Maximum value of depth*maximum(velocity, 1.0 m/s) downstream of the junction of the Karli River with the Jhelum River for rapid disintegration of the landslide dam using a 50 m/hr downcutting rate.
Figure 42. Maximum velocity downstream of the junction of the Karli River with the Jhelum River for rapid disintegration of the landslide dam using a 50 m/hr downcutting rate.