A Summary of the Sentinel Slide Project
Zion National Park

Reoccurring landslides along the Zion Canyon Scenic Drive have required some creative solutions for maintaining a road in a location that is geologically active.

Original Slide

A massive landslide occurred as a rotational block failure and/or general collapse of a high ridge about 7,000 years ago near a formation now called The Sentinel. A large ridge of Navajo Sandstone collapsed along with the underlying keyenta and moenave formations filling Zion Canyon to a depth of about 500 feet over a distance of about 1 mile. The rock movement may have begun as deep as the chinle formation (widely known for its susceptibility to landslides) or the overlying Moenave formation. The slide dammed the North Fork of the Virgin River forming a lake about 300 feet deep at the downstream end, and pooling water back into the narrows.

The narrow lake would have filled with water in about one year, overtopping and beginning to cut into the dam. However, the process of cutting away the dam proceeded slowly due to its massive size and abundance of large rocks in the slide debris. As the smaller material is carried away, larger rocks fall into the channel and armor it. This process can be viewed today south of Birch Creek where large boulders line the river channel, and it is obviously much steeper than river segments upstream and downstream of the slide. An estimated ½ of the volume of the slide has been carried away by the river. Lakes caused by slides of a similar nature, though generally smaller in size, have occurred in several places in the canyons of Zion National Park.

The approximate age of the slide has been determined by radiocarbon dating of bits of organic material found in the lakebed sediments. The Utah Geological Survey conducted core drilling in May 1997 at the downstream end of the lake. Two samples of organic material from the fine clay of the lakebed sediments dated to 7,150 ± 810 and 6,800 ± 580 years before present. A sample collected from near the top of the lakebed sediments (~100 feet above current river level in Burch Creek) by Wayne Hamilton was dated to 3,600 ± 400 years ago, and is thought to represent some of the last lakebed sediments to accumulate before erosion into the landslide dam began to appreciably lower the lake level. Based on these dates, fine sediments accumulated in the lake for about 3,000 to 4,000 years. Once the level of down cutting through the dam reached the level of the sediments filling the bottom of the lake, the river flowed continuously with no standing water and fine sediments were no longer deposited. The river has cut over 100 feet into the landslide dam. Today, a mantle of sandy river sediments caps the underlying lakebed clays.

Recent Activity

On April 12, 1995, about 110,000 cubic yards of rock and sand slid downward as mass, pushing into the channel of the North Fork of the Virgin River. A stream gauge downstream recorded an abrupt cessation of stream flow at 9:20 pm as the river had been dammed to a depth of about 15 feet. Campgrounds downstream were evacuated due to the risk of flooding if the dam breached abruptly. This did not happen, but in about 90 minutes the small lake behind the dam filled to the point that the roadway, now the lowest path for the water, acted as a spillway. About 600 feet of roadway was eroded away along with power, sewer and water lines.

Historic Activity at the Sentinel Slide and the Water Connection

Prior to the 1995 slide, two previous slides occurred that were serious enough to block the road at the same location in 1923 and 1941. Both 1941 and 1995 had exceptionally wet winters (both were El Niño years). (Precipitation measurements were not made in Zion in 1923, but it was also an El Niño year and discharge in the Virgin River was very large in 1922 and 1923.) January through April precipitation was 11.85" in 1941 and 15.29" in 1995, compared to average precipitation for those months of 6.52." Combine this with the observation of seeps from the up and downstream ends of the slide, and from the rock cliffs downstream, and it is apparent that groundwater contributes to the slide by adding weight to the slide mass, lubricating the slip plain, and possibly lifting the slide mass with hydrostatic pressure.

Road Reconstruction and Protection

A temporary road passage was excavated in a few days, permitting emergency access to the lodge. Then during the winter of 1996 a 450-foot by 25-foot high retaining wall of concrete T-blocks[1] was constructed to support the road, a river channel capable of conveying a 100-year flood was excavated, and a rock buttress was added to the toe of the slide. The buttress is a dam of heavy basalt boulders at the toe of the slide, which act as a counterweight to reduce the risk of renewed sliding. The new road and channel had shifted 60 feet east around the slide debris.

The channel was ripraped to protect it from scour, but it soon became apparent that even moderate flows in the river had the energy to strip out much of the riprap. Observations in early 1998 showed that much of the riprap had been carried downstream by the river.

On September 11, 1998 a series of nighttime storms on already wet ground produced a flood of 4,500 cubic feet per second (cfs). This was a very short duration flood, rising sharply from 193 cfs at 8:45am to 4,500 cfs at about 10:00am, and then dropping to less than 1,000 cfs by noon. During that time the channel scoured down at least 6 feet, undermined the retaining wall and removed much of the gravel backfill. Depressions were observed in the road by 11:00am and a large sinkhole opened up in the roadbed minutes later. Later core drilling would document void spaces along the entire length of the wall.

Investigations showed that the wall had no provisions protecting it from channel scour. It was also found that the channel was so smooth, narrow and steep that it produced extreme water velocities and "supercritical" flow conditions that could move all but the largest boulders. More disturbing was the fact that a flood of this size has occurred on average every 12-15 years, far to frequent for damage of this magnitude to be tolerated.

A two-phased project was undertaken to repair the wall and correct the deficiencies. Phase I was the disassembly of the retaining wall, installation of a 20-foot deep secant pile wall (a curtain of overlapping 30" diameter holes drilled into the underlying slide debris and grouted with concrete) followed by reassembly of the retaining wall. It was accomplished during the winter of 1999. The piles are designed to provide protection from an additional 12 feet of channel scour.

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[1] "T-Blocks" are made of pre-cast concrete with a face that looks like stone masonry and a leg that extends several feet back under the roadway. These legs lock together and are backfilled with coarse gravel to provide stability and free drainage.

Sentinel Slide shortly after slide movement on April 12, 1995. The river is now flowing in what used to be the road bed. It previously flowed on the west side of the stone retaining wall now visible on the far side of the river. The objects in the river bed are water, sewer and electric lines that had been buried in the road bed.

Road Damage from scour under retaining wall and road during flood of September 1998.

Phase II involved widening and increasing the roughness of the river channel to reduce flow velocities during floods. Initial modeling of a widened channel showed disappointingly little reduction in flow velocities, with peak velocities during a 100-year flood event reduced only from 33 feet/second to 27 feet/second. It was realized that without increasing channel roughness, flow was continuing to be supercritical (somewhat analogous to supersonic movement in air) and not taking advantage of the widened channel. Supercritical stream flow behaves as a jet of water passing quickly through the center of the channel, while expending little energy flowing around irregularities in the channel. In contrast subcritical flow swirls around channel irregularities expending a substantial amount of energy as turbulence. As a result, modeling of a rougher channel showed peak velocities reduced to about 16 feet/second.

In order to get an idea of how wide to make the channel, the width of the natural channel several hundred feet upstream of the slide was measured. It was found that channel width during a 25-year flood averaged 67 feet in a natural channel, and only 39 feet where constricted by the Sentinel Slide. It was also found that during floods the constricted channel pooled water upstream of the slide. This had the effect of causing the gravel and cobbles to drop out of the flow and widen the channel. It also raised the water surface elevation, which would provide additional energy for scour as the water descended through the narrow section. The pooled channel was nearly twice as wide as the natural channel for the same flows.

It was therefore decided to widen the channel 20 feet, while adding large rocks and drop structures to achieve a roughness similar to natural channels. Further widening would have been desirable to alleviate hydraulic concerns, but would have further reduced the safety factor for renewed movement of the slide. The project was implemented during the spring of 2000. It entailed removing the existing rock buttress in 15-foot segments, removing 20 feet of slide material, and then reconstructing the rock buttress. Drop structures made out of boulders and additional boulder clusters were placed in the channel to increase roughness.

Discussion

The major challenge in this project is achieving a balance between the risk of failure from scour in the steep narrow channel, and the risk of failure due to further movement of the landslide. Cutting away the toe of the landslide to widen the channel reduces the stability of the remaining slide material. During the initial project design, the risk of additional sliding was given the greatest consideration because the recent slide was fresh in everybody's memory. After the river demonstrated its power to scour the channel, it was realized that some additional risk of slide movement would have to be accepted in order to create acceptable flow conditions.

The widened channel conveyed floods in October and November 2004, and January 2005 fairly well. These are the first significant floods since the 1998 flood that damaged the retaining wall, and are of comparable magnitude. Scour of gravel bars upstream of the slide indicate that no pooling occurred. Two of the four drop structures were disrupted, but the boulders remain and continue to contribute to channel roughness.

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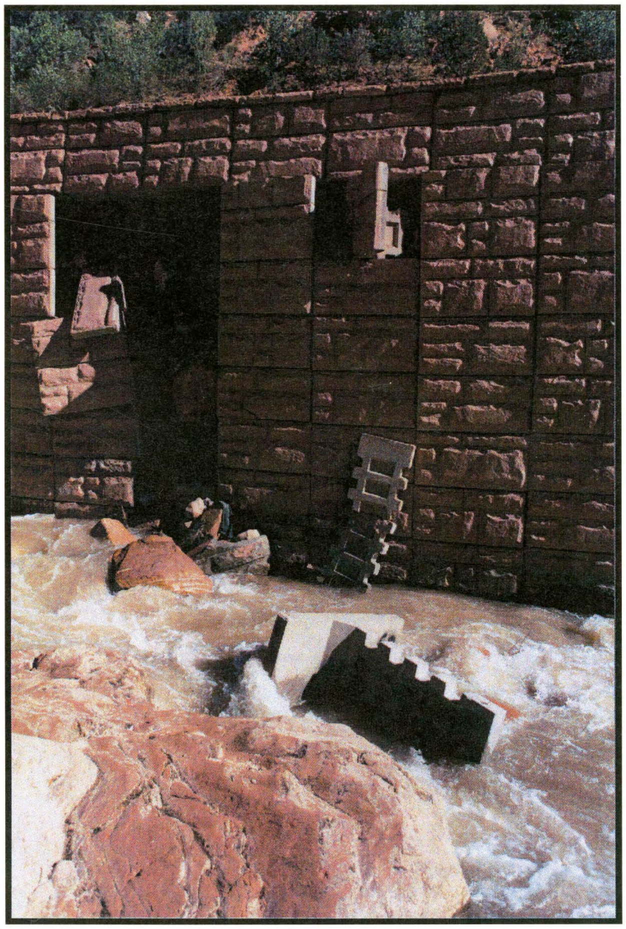

Damage to the retaining wall from scour during the September 1998 flood event.

Construction project to widen the river channel between the slide buttress and retaining wall in 2000. The approximately 40-foot wide channel was widened by an additional 20 feet, and boulder drop structures were added to increase channel roughness.

References

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