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H-2 LANDSLIDE RISKS

H-2.1 Key Concepts

Many dams and reservoirs are constructed in steep mountainous terrain where landslides can occur. Landslides, if large enough, can affect the safety of a dam or reservoir if they fail or move. Landslides can be triggered by heavy rainfall, snowmelt, reservoir drawdown, or large earthquakes. Ancient landslides can be reactivated, or if the geologic conditions are adverse, new landslides can be triggered. For new landslides to develop, typically something has to have changed over the thousands of years that the area has been exposed to floods and earthquakes, such as impoundment of the reservoir, excavation of a new road cut, or other disturbance to the area. Landslides can occur upstream in the reservoir, in a canyon downstream of a dam, or even within the abutment of a dam.

A landslide failing into the reservoir, if close enough, large enough, and moving fast enough, can generate a wave large enough to overtop a dam. Sloshing back and forth in the reservoir can result in multiple waves overtopping the dam. If the waves are large enough, downstream consequences can result just from the downstream overtopping flows even if the dam does not fail. If enough large waves overtop an embankment dam or a concrete dam with erodible abutments, an erosion failure could potentially result.

A landslide occurring downstream of a dam can block the river creating a debris dam. Subsequent releases from the dam can overtop and erode the debris dam, sending a large slug of potentially life-threatening flows downstream. While this can occur whether or not there is a dam upstream of the landslide, having an upstream dam creates additional complications. If there is damage to the upstream dam, say from large earthquake ground shaking, it may not be possible to lower the reservoir for fear of overtopping the debris dam. If the landslide was triggered by a large rain storm, the flood operating curve for the dam may dictate large releases that could overtop and fail the debris dam.

In some cases dams have been built abutting against a landslide. Often, these are ancient landslides that have stopped moving, or are moving very slowly. However, if such a landslide moves far enough, it can crack the core of an embankment dam, resulting in pathways for internal erosion to initiate, or disrupting the abutment support of a concrete dam, resulting in cracking and structural collapse of the concrete.

H-2.2 Landslide Stability

It is necessary to evaluate the stability of a landslide under various loading conditions that could impact a dam prior to analyzing the associated risks. It is not the intent of this section to describe in detail how to do this, as other documents and references are available for this purpose (e.g., Cornforth 2005). It is important to understand the geology and past performance (e.g., movement surveys and associated reservoir, precipitation, and groundwater conditions) of the landslide area to the extent possible. Limit equilibrium analyses can help to calibrate to the observed behavior and gain a relative sense of the effects of various loading conditions. It is important to consider three-dimensional effects in such analyses. For example, faults and other rock structure may control the direction of movement of a landslide mass, and if so, these features must be included in the analysis. The use of reliability analyses (see "chapter A-7, Probabilistic Approaches to Limit-State Analyses) can also be considered to estimate the likelihood of sliding under various loading conditions.

Landslides have been classified by Cruden and Varnes (1996) according to their velocity. This is classification system is shown in table H-2-1. The more rapid the movement, the more dangerous the slide.

Table H-2-1.—–Landslide Velocity Classification (Cruden and Varnes 1996)

Descriptor	Velocity Range
Extremely Rapid	> 5 m/sec
Very Rapid	3 m/min – 5 m/sec
Rapid	1.8 m/hr – 3m/min
Moderate	13 m/month – 1.8 m/hr
Slow	1.6 m/yr – 13 m/month
Very Slow	16 mm/yr – 1.6 m/yr
Extremely Slow	Negligible – 16 mm/yr

Under earthquake loading, the likely amount of displacement can be estimated using the methods described by Jibson (2007). Regression equations were fit to Newmark sliding analysis results using a large variety of ground motions and yield accelerations. The resulting equation of most use is given below:

$$\log D_N = 0.215 + \log\left[\left(1 - \frac{a_c}{a_{\max}}\right)^{2.341}\left(\frac{a_c}{a_{\max}}\right)^{-1.438}\right] + 0.51$$ **Equation H-2-1**

Where D_N is the estimated displacement in cm, a_c is the yield acceleration, and a_{max} is the peak horizontal ground acceleration of the ground motion being considered. If the seismic hazard has been de-aggregated to indicate the moment magnitude **M**, that contributes most to the risk, a better estimate of the displacement can be obtained from:

$$\log D_N = -2.710 + \log\left[\left(1 - \frac{a_c}{a_{\max}}\right)^{2.335}\left(\frac{a_c}{a_{\max}}\right)^{-1.478}\right] + 0.424M + 0.454$$ **Equation H-2-2**

H-2.3 Overtopping due to Landslide-Generated Waves

There are several methods available to estimate the height of landslide-generated waves at a given point in a reservoir relative to the landslide. A relatively simple equation was developed for Morrow Point Dam based on laboratory hydraulic model studies (Pugh and Chiang 1986), and assuming rapid failure of the slide mass. Although the equation was developed for a specific geometry, it seems to predict reasonably well the wave heights experienced at other sites.

$$\frac{\eta}{D} = 0.14\frac{\sqrt{\frac{V}{D^3}}}{10^{\frac{L/D}{58}}}$$ **Equation H-2-3**

Where η is the wave height at the dam, D is the reservoir water depth at the Landslide, V is the volume of water displaced by the landslide (usually taken to be the slide volume), and L is the distance from the landslide to the dam (use consistent units). This formula was based on displacement of the water by intact slide blocks. Another set of equations for predicting wave heights for debris slides is provided by Huber and Hager (1997), again assuming rapid movement of the landslide. The "displacement number" is given by the following:

$$M = \frac{V_S}{bd^2}$$ **Equation H-2-4**

And the wave height is given by the following:

$$H = 1.76d(\sin\alpha)\cos^2\left(\frac{2\gamma}{3}\right)\left(\frac{\rho_S}{\rho_W}\right)^{1/4} M^{1/2}\left(\frac{r}{d}\right)^{-2/3}$$ **Equation H-2-5**

Where V_S is the landslide volume, b is the landslide width, d is the water depth at the landslide, α is the landslide failure plane angle from horizontal, γ is the angle between the direction the landslide moves and the direction of propagation to the dam, ρ_S is the density of the landslide material, ρ_W is the density of water, and r is the distance from the slide to the dam. A more recent paper by Perez et al.(2006) may also prove to be useful, to help in establishing a possible range in combination with the other equations.

H-2.3.1 Event Tree

Since each landslide is unique, the event trees for evaluating associated dam safety risks will also tend to be unique. Therefore, it is important to identify and describe the potential failure modes as described in "chapter A-3, Potential Failure Mode Analysis". Figure H-2-1 shows an event tree for a landslide-generated wave at a concrete arch dam that could be triggered by rapid lowering of the reservoir. In fact, a reservoir drawdown was planned in order to perform some maintenance on the powerplant intake and trashracks. The Standard Operating Procedures limited the drawdown to less than 3 ft/day, and in fact drawdown rates had never exceeded 2 ft/day over the life of the project. However, a faster drawdown was needed for the maintenance in order to provide the time needed to complete the work before the runoff season.

The tree shows 100 percent of the drawdown in the rate of 3 to 6 ft/day, based on the maintenance schedule, which indicated a drawdown of 4 to 5 ft/day is needed to complete the work. An upper branch with drawdown at > 6 ft/day was also estimated (though not shown on figure H-2-1) since there was an indication that the drawdown may need to be more rapid if it started later than anticipated. However, it was always intended that only one of the branches would be active (i.e., assigned a 100 percent probability) for any given run.

There is a large landslide on the right bank of the reservoir less than a mile upstream of the dam. The lower, smaller part of the slide near the reservoir (labeled "Primary A" on figure H-2-2) appears to be less stable than the upper part (labeled "Secondary A" on figure H-2-2), based on the slide geometry and surveyed movements, which show the lower part creeping under normal reservoir conditions. The event tree looks at the probability of the entire slide (i.e., both Primary A and Secondary A) failing into the reservoir, versus only the lower part failing into the reservoir. The likelihood of the landslide moving rapidly was estimated based on recorded landslide movements and results from limit equilibrium analyses. Due to the relative stability of the upper part of the slide, the likelihood of the entire mass sliding into the reservoir was estimated to be unlikely, while there was not clear evidence to suggest the lower part of the slide would move rapidly or slowly if it failed.

Estimates of wave height suggested that the chance of a wave generated by the lower portion of the slide overtopping the dam was remote. However, if the larger mass failed suddenly, a wave approaching 50 feet high could be generated at the dam at any time during the drawdown. For the large landslide, wave height

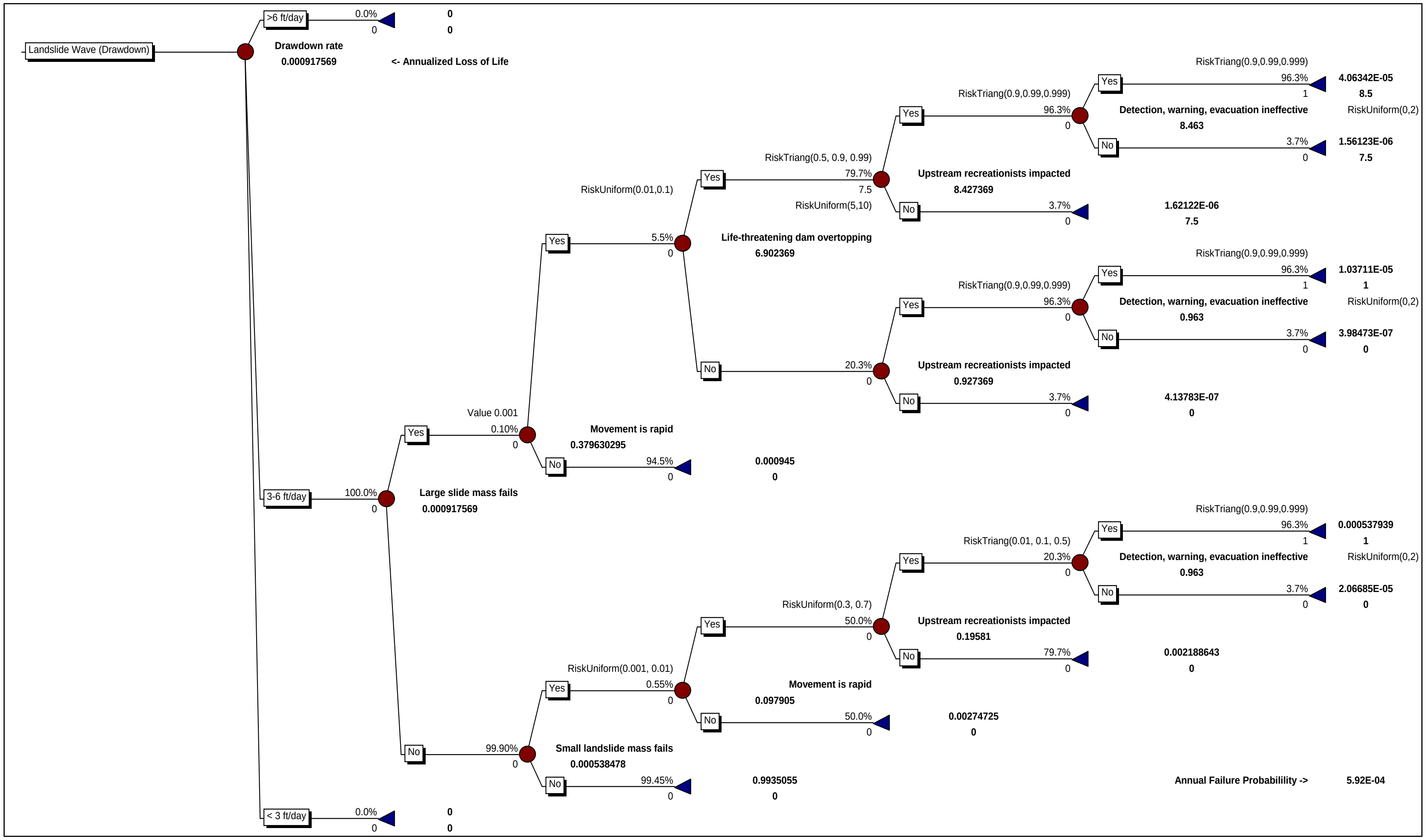

Figure H-2-1.—Example landslide event tree.

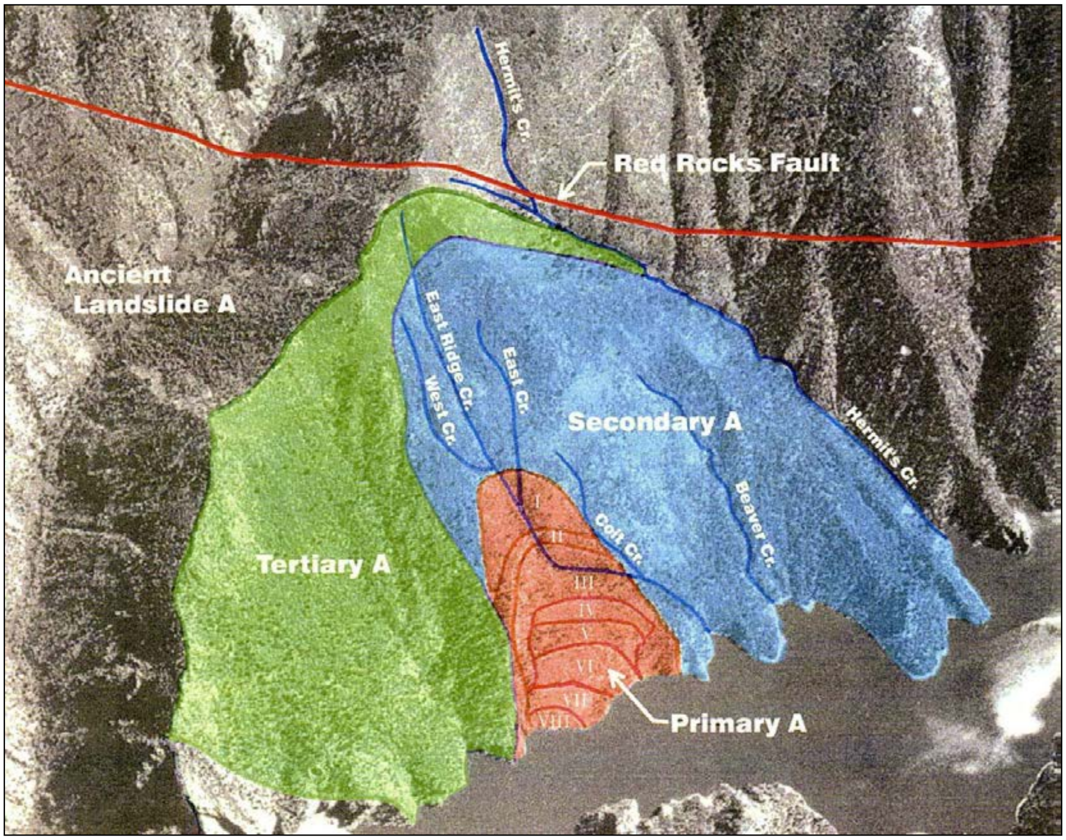

Figure H-2-2.—Landslide masses for example (Primary A is lower portion experiencing largest movements, Secondary A is upper portion experiencing slower movements, and Tertiary A does not appear to be moving).

calculations and limit equilibrium analyses were performed for various drawdown depths, and the results used to estimate the reservoir range during the drawdown when failure is most likely to occur, and what the range in wave overtopping depth would most likely be at about that reservoir elevation range. While failure of the dam under this condition is remote, the wave itself could be life-threatening to people visiting the canyon downstream, including those in a campground near the river a few miles downstream.

There are boaters and fishermen on the lake. Any type of landslide failure has the potential to impact them. It was judged that capsizing at least one boat was likely under any rapid landslide scenario.

Note that the event tree contains consequences midway through the top branch, not just at the end. This is needed since recreationists on the reservoir would be impacted from a large landslide whether or not a wave went over the dam. The only thing to be aware of in this case is that the annual failure probability requires summing all the ending probabilities following the internal node where consequences are specified, because life threatening failure has occurred at that point.

A similar event tree can be used to evaluate landslide risks under hydrologic or seismic loading. Instead of drawdown ranges, seismic or hydrologic load ranges are used.

H-2.4 Overtopping Erosion of Downstream Landslide Debris Dam

Since this potential failure mode is not directly related to the dam upstream, and since the loadings needed to generate such a situation would need to be larger than experienced since canyon formation, it is not discussed in detail here. However, operational releases from the dam could result in overtopping erosion failure of the debris dam and a sudden surge of water downstream. For this reason, there may be pressure on the dam operators to hold back the downstream flows. If the flows cannot be held back, it will likely become the task of the dam operators to issue warnings. For this reason, it is a good idea to understand the geology in the canyon downstream and the potential for this type of potential failure mode to develop.

H-2.5 Embankment Disruption Leading to Internal Erosion

If a landslide moves within the abutment of an embankment dam, it can cause disruption and cracking of the embankment core and subsequent internal erosion through the cracks. If a thin upstream member, such as a reinforced concrete facing, forms the water barrier for the dam, landslide movement can lead to buckling of the slab, and flow through large cracks, which may be capable of eroding even large rockfill forming the downstream shell. If the abutment of an embankment dam contains a landslide, limit equilibrium analyses, including possibly reliability analysis, can be made to estimate the likelihood of the landslide moving under various loading conditions (i.e., earthquake load ranges, flood load ranges, and/or ground water ranges). These load ranges can be put on the front end of an event tree and the likelihood of cracking estimated for each. Given cracking, the methods outlined in the “chapter D-6, Internal Erosion Risks for Embankments and Foundations,”can then be used to estimate the likelihood of failure.

H-2.6 Cracking and Disruption of a Concrete Dam

If a landslide exists in a concrete dam foundation, movement can also cause cracking of the dam. Similar methods to those summarized above for embankment dams can be used to evaluate the potential for movement, except that internal erosion is not the issue, but adverse cracking, isolation, and displacement/rotation of the isolated blocks of concrete in the dam could be. (See the "chapter E-4, Risk Analysis for Concrete Arch Dams" for some ideas on how to evaluate the risks associated with this.) If movement of the landslide results in loss of abutment support, such that the dam moves with the landslide, the methods in "chapter E-4, Risk Analysis for Concrete Arch Dams" related to sliding of foundation blocks can be used to evaluate abutment stability and potential risks.

H-2.7 Loss of Release Capacity

If a landslide is triggered by a large rainstorm, damage to a spillway or other outlet features can occur at the same time that large reservoir inflows are occurring. If the landslide debris blocks the spillway or intakes, or damages them to the point that they cannot be operated, then premature overtopping of the dam may occur.

H-2.8 Resources

There is ongoing research associated with landslides and their associated risks. The information is not necessarily specific to landslides as they relate to Dam Safety, but does provide guidance and information that might be useful in evaluating the risk or rate of landslide movement. This list not inclusive of all resources available, but provides some initial guidance that may assist in developing risk estimates associated with landslides.

- "Recommendations for the Quantitative Analysis of Landslide Risk" (Corominas et al. 2013) discussed, in detail, the data and analysis relevant to assessing the risks association with landslides. This information is available at: https://paperity.org/p/35203471/recommendations-for-the-quantitative-analysis-of-landslide-risk

- The United States Geological Survey (USGS) has developed landslide hazard maps for the United States and an archive of landslides that have occurred worldwide since 2004, and provides valuable information on initiating events and rate of movement. This information is available at: http://landslides.usgs.gov/hazards/

- The Landslide committee of the Canadian Geotechnical Society contributes to the Canadian National Landslide Guidelines and collaborates with other professional societies on current state of the practice in the evaluation of landslides. This information is available at: https://www.nrcan.gc.ca/hazards/landslides.

H-2.9 Relevant Case Histories

H-2.9.1 Vaiont Dam: 1971

Vaiont Dam is an 870-foot-high concrete arch structure completed on the Vaiont River near Longarone, Italy. The entire left side of the reservoir was formed by steep slopes in bedded limestone with clay interbeds. The reservoir started filling in February 1960, and the dam was completed in September 1960. In October 1960 after a period of heavy rain, benchmarks installed on a suspected landslide mass began to accelerate, and a crack formed along the reservoir. The next month, a slide of 700,000 m^3 hit the reservoir, creating a 2m high wave at the dam. The reservoir was lowered and various studies were undertaken. Exploratory adits were driven, piezometers were installed, and a bypass tunnel was driven to connect the upper reservoir and lower reservoir in case a slide separated the two. For the next three years the level of the reservoir was adjusted to try and limit the slide movement. Then on October 9, 1963, a massive slide of 350,000,000 yd^3 (a mile wide and a mile high) slid into the reservoir just upstream of the dam (at a minimum distance about the height of the dam) at an estimated 20 to 30 m/s. A wave washed up the right bank more than 850 feet, nearly to the town of Casso high on the abutment. A control building on the left abutment and an office/hotel 180 feet above the dam crest on the right abutment were demolished and 60 staff perished. Water surged back across the canyon and up the left abutment, and a wave about 330 feet high washed over the top of the concrete dam. The wall of water was still over 230 feet high when it hit the village of Longarone about a mile downstream. The village was wiped clean, and about 2,600 people lost their lives. The dam survived the overtopping, but the reservoir was filled for about a mile upstream of the dam, and it had to be abandoned.

Post-failure investigations showed that low strength clay layers existed between the limestone beds. It was surmised that rainfall in the mountains above the reservoir was conveyed through solution features to the reservoir slopes where it became trapped by the impermeable clay layers. A review of the landslide survey data showed that movement accelerated with a high reservoir level following periods of heavy rain. Thus, it was the combination of high reservoir level which unweighted the toe of the slide, and heavy precipitation which increased the pore pressures in the slope, that lead to triggering of the slide on weak clay layers. This was confirmed by limit equilibrium analyses that considered side constraint afforded by a fault on the upstream side of the landslide mass (Hendron and Patton 1985).

H-2.9.2 Madison Canyon Landslide: 1959

A large landslide was triggered by the M7.7-7.8 earthquake that occurred near Hebgen Lake in the southwest part of Yellowstone National Park. Approximately 43,000,000 yd^3 of material slid across the Madison River Canyon, downstream of

Hebgen Lake Dam, outside the west entrance to the park. Landslide debris traveled about 400 feet up the opposite side. Unfortunately, there was a campground at this location, and 27 people lost their lives. The landslide occurred where no slide had previously existed. A “dike” of dolomite buttressed a unit of metamorphic schist and gneiss, which formed most of the mountain. The foliation in the metamorphic rock dipped about 50 degrees toward the river. The shaking was apparently sufficient to cause collapse of the dolomite, allowing large scale sliding on the weak foliation planes. A landslide debris dam, about 200 feet high and 4,000 feet wide, was formed across the river. Impervious weathered rock and debris was deposited upstream such that leakage through the debris dam was limited to about 200 ft^3/s. Hebgen Lake was nearly full at the time of the earthquake, and Hebgen Lake Dam was damaged. Drawdown of the lake was necessary to inspect the dam and make repairs, but the volume of water in the reservoir was nearly 4 times the volume that could be stored in “Quake Lake” behind the debris dam. Even without draining Hebgen Lake, Quake Lake would fill and overflow from the natural stream flows in three to five weeks. To solve this problem, the USACE quickly cut a spillway channel 250 feet wide through the debris dam, capable of passing 10,000 ft^3/s, and armored it with rip-rap. Later, the spillway channel was lowered, reducing the volume of Quake Lake from 80,000 acre-ft to 36,000 acre-ft (Barney 1960).

H-2.10 References

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