Damage Evaluation of the Taum Sauk Reservoir Failure using LiDAR

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ABSTRACT: The Taum Sauk Dam Upper Reservoir located in southeast Missouri failed on December 14, 2005. Two days after the catastrophic failure event an aerial survey were conducted to collect Light Detection and Ranging (LiDAR) data. The LiDAR data were interpreted and evaluated to a sub-meter resolution. The data were used to quantify the extent of the damage produced by the water released into a Missouri State Park. Damage consisted of washing out trees, soil, and the reservoir embankment, and scouring the ground to bedrock in places. Additionally, the data also were used in the evaluation of the reservoir damage, which consisted of a 207.3m (680ft) wide breach and scoured slopes. This paper focuses on the multiple uses of LiDAR data to assess damage to natural resources, and hydraulic and geotechnical evaluation of the failure.

INTRODUCTION

During the early morning hours of December 14, 2005, the Taum Sauk Upper Reservoir rock-fill dike underwent a catastrophic failure, releasing about 1.5 billion gallons of water down the northwest side of Proffit Mountain. The release of water downstream stripped the land of existing vegetation and soil cover, and demolished one residence directly in the flood path. Severe flash flooding was experienced on the East Fork of the Black River, including Johnson's Shut-Ins geological features and Johnson's Shut-Ins State Park campground. Figure 1 is an aerial photograph showing the consequences of the water release, the breach area in the upper reservoir, and a portion of the flow path downstream with exposed bedrock and sedimentation due to the flood waters.

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FIG. 1. The upper reservoir breach and a portion of the flow path
(photo courtesy of J. Spooner, 2005)

The breach occurred along the northwest radius of the upper reservoir over a distance of about 680 feet at the crest and through the entire height of the reservoir. On the morning of the failure, water began overtopping the reservoir. This process continued until the rockfill embankment failed catastrophically, sending a torrent of water down into the Missouri Department of Natural Resources park. Another view of the damaged area at the breach location is shown in Figure 2. Here the camera points down stream towards the flow path with a closer look of the exposed bedrock and flood sediments (exposed soil/rock and embankment rockfill material). Notice the decrease in valley floor slope where sediment deposition begins.

FIG. 2. Sedimentation and flow path looking northwest from breach location.
(photo courtesy of D. Hoffman, 2005).

An early response team formed from the partnership between the U.S. Geological Survey (USGS), Mid-Continent Geographic Science Center and the University of Missouri-Rolla (UMR), Natural Hazards Mitigation Institute, completed damage reconnaissance activities after the initial emergency operations were completed. The ground activities took place during the mornings of December 15 and 18, 2005. The damaged areas were surveyed using ground based Global Positioning System (GPS) mobile units and an aerial LiDAR sensor system on an aircraft. This paper discusses the different ways in which these data were used to evaluate the damage and study the consequences of the upper reservoir failure. The topics discussed herein are those related to the surface water modeling, sedimentation analysis of the flow, and engineering evaluation of the upper reservoir breach.

GEOLOGIC SETTING

The St. Francois Mountains region is a unique area consisting of Missouri's oldest landscape. During the Precambrian time igneous granite rock formed as a molten magma crystallized deep within the earth's surface. Volcanoes closer to the surface also began to erupt large quantities of pyroclastic flows and rhyolitic lava (Unklesbay and Vineyard, 1992). Thick layers of pyroclastic materials were deposited throughout the region as either air fall or ash flow tuff. Residual heat from the eruptions often melted or "welded" the pyroclastic ash fragments together and cooled to form a hard igneous rock known as welded tuff. Most of the ash flow tuff present in the Proffit Mountain region is reddish in color and of felsic or rhyolitic composition. Various rhyolites and tuffs have a cumulative thickness of several thousand feet in the St. Francois Mountains. Many large bodies of reddish to grayish granite are included within this material.

After the decrease and eventual halt of volcanic activity during the Precambrian time, the area was subjected to the Ozark dome uplift (Unklesbay and Vineyard, 1992). The uplift, as well as erosion, formed the igneous knobs and ridges common to the St. Francois Mountains of today. When the Cambrian seas began to rise, much of the region became blanketed by water, leaving the igneous knobs and ridges as highpoints or islands. Deposition of sedimentary rocks during this period left thick layers of sandstone and carbonate sediments on the sea floor that draped the slopes of the igneous highpoints and knobs.

Regression of the Cambrian seas exposed the younger sedimentary deposits and the igneous highpoints. Erosion and weathering of the Cambrian rocks cut distinct drainage patterns through these sedimentary deposits. Present day drainage patterns preferentially cut through sedimentary deposits down to underlying steep granite ridges. These ridges resist the effects of weathering and erosion more than the younger, softer, sedimentary rocks. When rivers cut down into these ancient bedrock ridges, their flow is locally restricted, forming steep, closed in chutes called shut-ins. Johnson's Shut-Ins on the East Fork of the Black River is an example of this type of feature, and is located below the Taum Sauk Upper Reservoir. As with the most of the Ozark Plateau, the St. Francois Mountains were not glaciated during the Pleistocene. This preserved many ancient, deeply weathered zones of bedrock and soil, which are locally present throughout the region.

LiDAR RECONNAISSANCE SURVEY

LiDAR data were collected for a 81.6 km^2 (31.5 square mile) area including the Proffit Mountain Upper Reservoir, located in southeast Missouri. LiDAR are sensor systems that very accurately measure range or distance by sending out a pulse of laser light to the target and measuring the time for the reflected light to return. Topographic LiDAR systems use an infrared laser as a light source to measure the distance to the ground. Inertial measurement systems and GPS allow for the precise determination of the position of the sensor in the aircraft as it flies over the land surface. Laser pulse frequency, beam width, flying height, and data processing methods contribute to the determination of the resolution of the resulting elevation data. High accuracy bare-earth processed LiDAR data were created with values represented to the nearest centimeter. The elevation values are in Mean Sea Level, North American Vertical Datum 1988 (NAVD88). Horizontal coordinates are in Universal Transverse Mercator, Zone 15, North American Datum 1983. The vertical root mean square error (RMSE) of the digital elevation data is no more than 15.0 centimeters or better relative to NAVD88. The LiDAR data were captured at a nominal post spacing of no more than 0.7 meter. The LIDAR image shown in Fig. 3 displays a portion of the data acquired on the morning of December, 16, 2005.

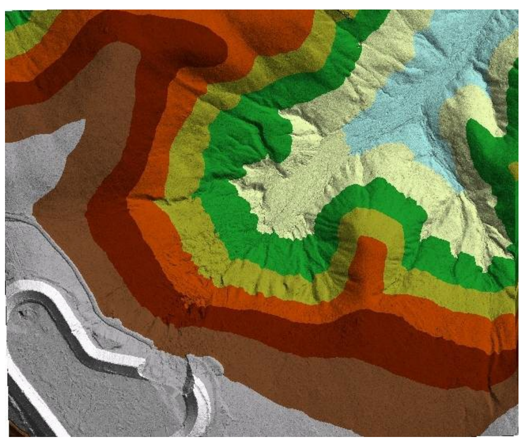

FIG. 3. LiDAR Image of the Taum Sauk Failure at about 25m intervals (note the upper reservoir breach in the lower left corner of the image).

LiDAR data met or exceeded relevant National Standard for Spatial Database Accuracy (NSSDA) requirements. The vertical bare earth accuracy of 15.0 cm RMS at 95% confidence level and horizontal accuracy of 0.5 meters RMS at 95% confidence level were met or exceeded in the final product.

DETERMINATION OF THE DAMAGED AREA USING GPS

On the day after the failure, the recon team implemented recently developed mobile Geographic Information System (GIS) data collection techniques to capture the debris flow perimeter from the Upper Reservoir breach within Johnson Shut-Ins State Park from Highway N to the Shut-Ins. These techniques were developed by the team during the Hurricane Katrina reconnaissance activities. A tablet PC used was built to operate in rugged environments, and the screen display was designed to be viewable in all lighting conditions including direct, bright sunlight. The integrated GPS unit combined with outdoor viewing capabilities allowed verification of the positions in real time by comparing plotted position to actual position on the high-resolution base imagery. This technology and its data collection capabilities will benefit the team in future emergency response scenarios.

The data collected in the field were used to create a polygon for use in a GIS and Google kml file for distribution to all team members in a timely fashion. Results were available to all team members in less than 12 hours. Combining this technology with other Bluetooth enabled equipment, such as laser rangefinders, can further enhance the reconnaissance response capabilities in the future.

SEDIMENTATION AND EXPOSED GEOLOGIC DEPOSITS

A 2.6 km (1.6 mile) long side canyon draining the western slope of Proffit Mountain was eroded locally of soil, colluvium, alluvium, and bedrock following the breach of the upper reservoir. Initial assessment of these post-failure erosional and depositional features was conducted by a team of UMR/USGS geologists. A site visit was made on December 21, 2005 to traverse the channel and make detailed field notes and sketches using topographic maps and unrectified oblique aerial photographs. Waypoints were collected along facies contacts using a Garmin eTrex handheld GPS unit. The waypoint file was converted to a shapefile to be used in the compilation of a draft geologic map. LiDAR and digital aerial photographs were also used in the post-field analysis. Rectified digital photography with a spatial resolution of 0.15 m (6 inches) was provided by MACTEC, Inc. Data fusion techniques were used to merge the multiple data sets allowing for maximum information content extraction during the interpretation phase. Additional field visits were made to verify and edit the draft map.

New exposures that were identified in the preliminary mapping investigation include Precambrian rhyolitic and granitic sequences, a highly weathered mafic unit, and a paleoweathered boulder field possibly representing a Cambrian-aged sea shore. Most of these Precambrian exposures occur in the upper third of the valley. Basal dolomite and sandstone sediments of Cambrian age lie in direct contact with the Precambrian rocks. The youngest units exposed in the valley include partially lithified valley fill colluvium and loose unconsolidated gravel alluvium. Various scour and impact features have been preserved in these younger sediments.

In contrast to the new bedrock exposures of the upper valley, the middle and lower valley segments were largely infilled with new sediment debris derived from the advancing flood waters. Sedimentary deposits differ in the middle and lower valley segments, being separated by a pronounced curve in the Proffit Mountain valley floor that reduced the subsequent downstream flow energy of the flood waters. In the upper segment of the valley, flood deposits are characterized by a basal layer of poorly-sorted and relatively fine grained (pebble to silt size) sediment (see Figure 4). This basal layer is overlain in sharp contact by a well-sorted layer of cobbles and boulders, from which finer grained material has been partially removed. These two layers appear to have been deposited in quick succession; the poorly-sorted basal unit by a forward advancing hyperconcentrated streamflow that was losing turbulent energy, and hence its suspended sediment load. The upper unit is interpreted to represent an advancing traction load of relatively coarse boulders and cobbles. Late stage erosion, dissection, and partial reworking of earlier deposited sediments occurred as progressively clearer flood waters washed over the earlier basal and upper units.

In the lower valley segment, cut bank and point bar deposits flank the pronounced valley curve. Near the mouth of the Proffit Mountain valley, where it enters the East Fork channel of the Black River, ripple-marked sand and silt deposits are inter-dispersed among boulders. These fines were deposited as late-stage flood waters entered East Fork Lake, a newly formed impoundment resulting from the temporary constriction of flood waters through the Johnson's Shut-Ins valley, and the formation of a boulder debris dam across the East Fork valley. A large scour feature also formed in the East Fork valley at a location directly across from the mouth of the Proffit Mountain valley. Most of the East Fork valley, however, (including the Shut-Ins) has been affected by debris infilling rather than erosion processes.


(a)

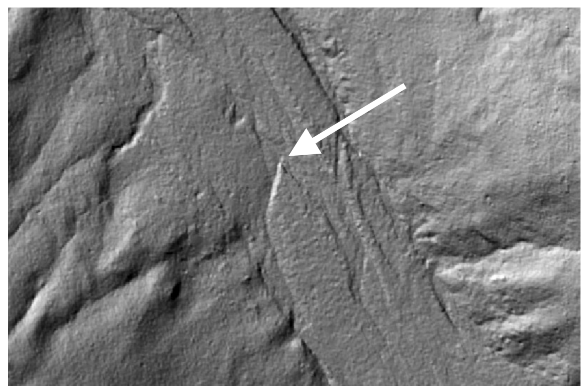
(b)

FIG. 4. (a) Poorly sorted lower basal deposits and upper well-sorted boulder deposit that has been dissected and exposed by later stage "clear water" flooding. Rebar fragment located in center portion of lower basal deposit is pointing downstream. (b) LiDAR image showing flood deposits traversing from lower right to upper center. Downstream direction is to the top of figure and the arrow shows location of photograph (a).

SURFACE WATER MODELING

Natural hazards, such as floods from dam failures, often occur suddenly and impact people, property, and have a permanent impact on the geomorphic landscape. Simulating retaining wall failure floods such as this provides important information concerning peak discharge magnitude and comparison to flood frequency estimates. In addition, volume estimates of debris movement and documentation of the retaining wall failure flood extent and flood frequency will provide information for re-habilitation of the Johnson Shut-Ins State Park.

Efficient and safe means of estimating peak discharge are required during flood hazards where conditions are impossible or impractical to measure directly. Indirect measurements of peak discharge make use of the energy equation and incorporate general factors such as the physical characteristics of the channel, the water-surface elevations at the time of peak flood stage, and hydraulic factors such as Manning's roughness coefficients and discharge coefficients based on open channel physical characteristics, water-surface elevation, and discharge (Rantz and others, 1982).

One indirect method used LiDAR data to define a table relating surface area to volume of the upper reservoir. The volume of the upper reservoir was correlated to the water surface elevation in the reservoir collected every 5 seconds during the failure, which was provided by AmerenUE. The volume per time analysis produced a retaining wall failure flood hydrograph with peak discharge; another indirect approach involved the slope-area method. This method is based on the uniform flow equation in which a drop in water-surface profile along a reach represents energy losses caused by bed and bank roughness. This method used LiDAR data to develop cross-sections that represented channel bed and overbank geometry. Cross-sectional geometry is required to identify area, hydraulic radius, and slope necessary to satisfy the fundamental Manning's equation used in the slope-area method.

Dynamic flood wave routing models use an input hydrograph to route the flood wave. Steady state models use peak discharge to develop flood profiles used to map inundation extents. LiDAR provides the geometric basis for contour data sets that are used in modeling, as well as point data necessary to create a triangulated irregular network (TIN) surface (Figure 5) used to produce flood inundation maps and qualitatively estimate the volume of debris movement.

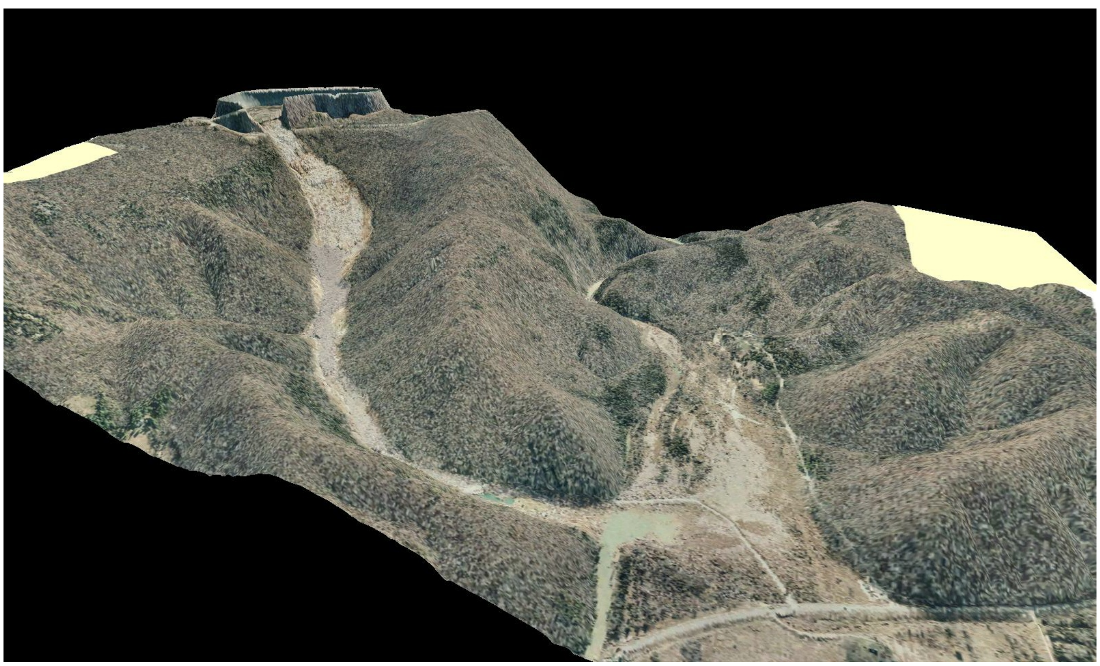

FIG. 5. High resolution imagery overlain on LiDAR derived surface (imagery courtesy of Sanborn Inc, proprietary to MACTEC, Inc.)

Use of pre- and post-processing software known as BOSS RiverCAD from BOSS International Inc., allowed a georeferenced and attributed contour data set to be input, and cross-sections to be cut in a manner perpendicular to conceptualized flow (Figure 6). The modeling effort analyzed each cross-section as a "slice" of flow in one dimension. All cross sections were combined and used with steady and unsteady flow simulations to produce hydrographs, flood profiles, and inundation extents. Volume estimates of debris movement were derived from differencing the LiDAR surface with a digital elevation model (DEM) surface before the failure. The approach was somewhat limited due to differences between the higher resolution LiDAR surface and the coarser resolution DEM surface. A publication of findings will be released on December 31, 2006.

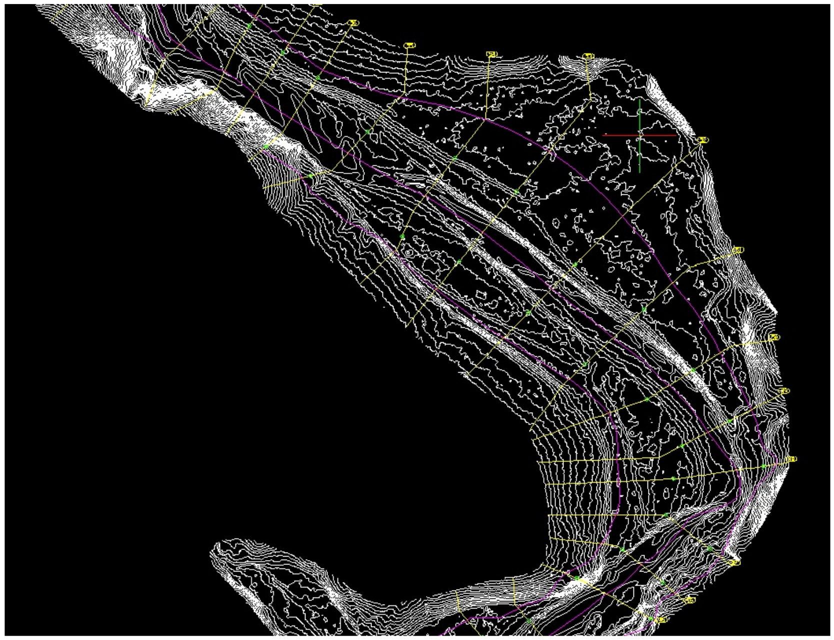

FIG. 6. Cross-sections developed from LiDAR derived contour data set.

ANALYSIS OF THE UPPER RESERVOIR FAILURE

Several approximations of the Upper Reservoir rock-fill dike breach area cross section were determined using site photography from the reconnaissance activities combined with additional information from Rizzo, 2006. The LiDAR survey allowed an accurate determination of post failure terrain elevations, orthophoto development, high resolution contour production, and bare-earth surface DEM construction. The generation of existing terrain cross sections, which represent the Upper Reservoir rock-fill dike as-built conditions, allowed accurate determination of the rock-fill dike cross section in the immediate vicinity of the breach area. Using the program ArcGIS 9.0 and the available LiDAR survey data, one-half meter contours were generated for areas of interest near the breach. From the generated contours, several cross-sections were generated. The generated contours and an example of a generated terrain cross section, are shown in figures 7 and 8. Similarly, the inclination of the bedrock foundation was determined at the exposed rock of the breach area. Several cross sections in the general area of the breach were generated, including the upstream slope, the downstream slope, the bedrock inclination, the crest width, and the base width. A typical Upper Reservoir cross section used for evaluation of failure mechanisms that involved slope stability and hydraulic analyses is shown in Figure 8.

The slope stability analysis revealed a calculated factor of safety of 1.5 with the reservoir at full capacity. Several conditions of the rock-fill embankment saturation were considered by varying the phreatic surface, and it was determined that at least a 24.4m (80ft) saturated zone in the upstream side to reach marginal instability. Since the rockfill material has a high permeability the earth structure is not able to hold that much water and it would drain out rapidly. This led the investigators to dismiss a global slope stability as a potential failure mechanism. The combination of overtopping, scouring, and undermining of the parapet wall atop the embankment appears to be the most likely mode of failure. Additional details on the evaluation of the Taum Sauk Upper Reservoir failure have been reported by others. (FERC, 2006; Rizzo, 2006; Witt and Hoffman; 2006; Gehring, 2006).

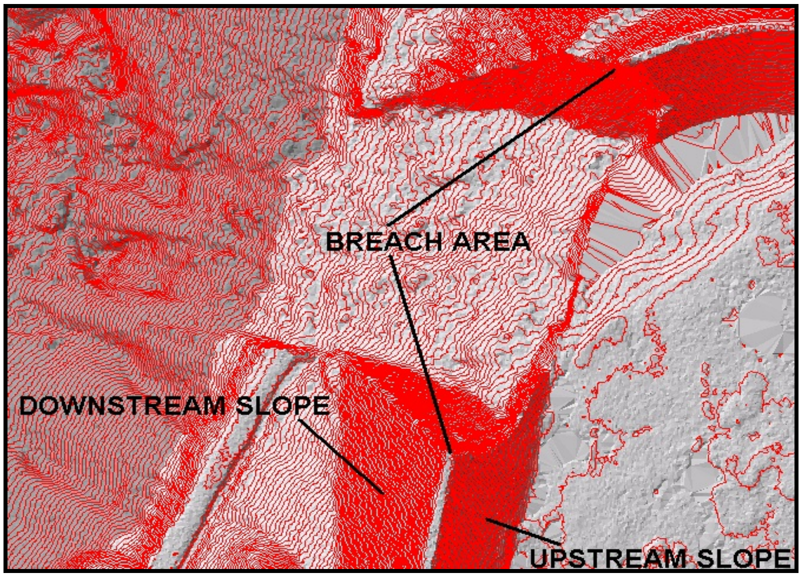

FIG. 7. Generated contours for analysis of upper reservoir breach area.

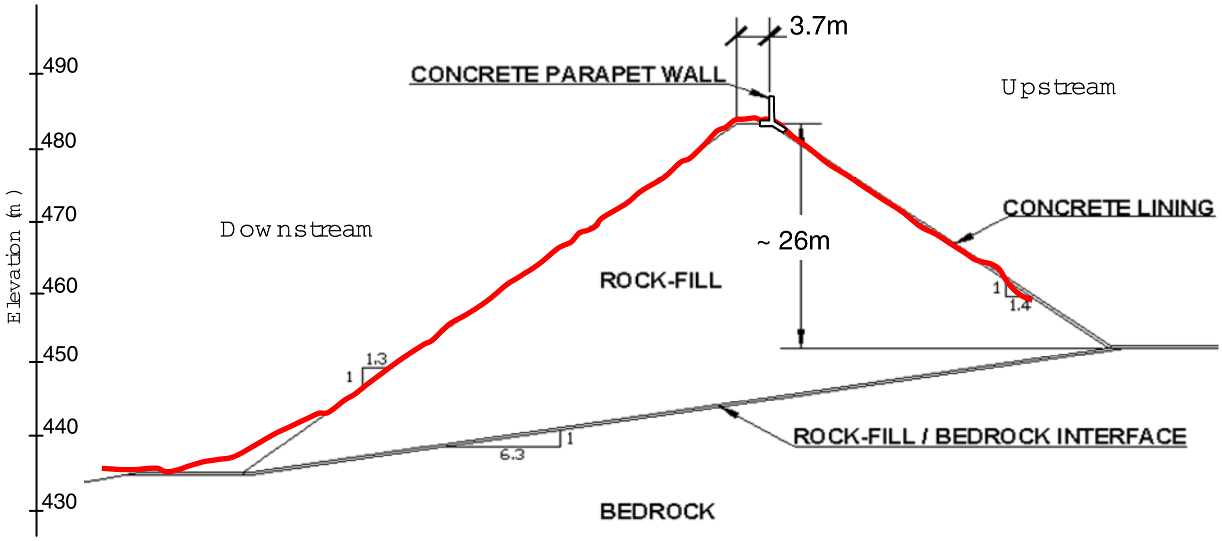

FIG. 8. Typical Upper Reservoir rock-fill dike cross-section and modeled layers based on LiDAR data (red profile line).

SUMMARY

In summary, the LiDAR data were acquired for general purposes, but primarily to document the extent of damage caused by the Taum Sauk Upper Reservoir failure. The relatively precise LiDAR elevation data were used efficiently by a multidisciplinary group of investigators. Data acquired in 1 day were used to determine high resolution elevation and spatial patterns shortly after the failure not possible with conventional techniques, and the data were subsequently used in different modes of analysis. The digital nature of the data allowed for data exchange within the high-speed network between the UMR and the USGS.

Three studies are summarized in the paper: sediment deposition due to the breach, surface water modeling, and geotechnical analysis of the Upper Reservoir. These are good examples of multidisciplinary work founded on the valuable LiDAR data.

The detailed studies that this paper summarized are currently underway and their findings will be presented in subsequent publications. Some of the issues related to the failure events are still being considered by the authorities.

ACKNOWLEDGEMENTS

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