WHEN AN ADJACENT WATERSHED INUNDATES YOUR OFFLINE RESERVOIR: UKUMEHAME RESERVOIR DAM REMOVAL CHALLENGES AND DESIGN

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ABSTRACT

Ukumehame Reservoirs Nos. 2 & 3 are a pair of offline reservoirs impounded by earthen embankments located on the island of Maui, Hawaii. The reservoirs were constructed during Hawaii’s sugar plantation era as a part of a statewide network of reservoirs and irrigation ditches to support local agriculture. In recent decades with the decline of sugar production, these and similar reservoirs are often neglected and have fallen into disrepair.

The reservoirs are classified as high-hazard due to a residential structure immediately downstream of the No. 3 embankment. In June 2008, a significant seep was discovered at the toe of the No. 3 embankment. Following this discovery, the reservoirs were drained and the dam owners decided to remove the reservoirs by breaching the embankments.

Hydrologic and hydraulic analyses led to the discovery that the probable maximum flood (PMF) within the adjacent stream overtops the embankments and inundates the reservoirs. We were challenged with designing breach sections to accommodate flows from the watersheds directly contributing to the reservoirs as well as flows from the overbank of the adjacent stream considering what we had learned about the PMF.

To better understand this condition, a 1D unsteady HEC-RAS model was created to simulate pre- and post-breach conditions. This analysis assisted in presenting the design of the reservoir removal to the owner and the State Dam Safety Division. A 2D HEC-RAS model was subsequently prepared for comparison with the 1D HEC-RAS model and the 2D model agreed with the conclusions drawn from the 1D model.

INTRODUCTION

History

Beginning approximately 180 years ago, sugar plantations and farming became a significant and integral part of the economy of the Hawaiian Islands. The first commercially successful sugarcane plantation was founded in Koloa on the island of Kaua’i in 1835 (U.S. National Park Service). Commercial production of sugar quickly grew to outpace the manpower of the local islanders, and beginning in 1850, foreign laborers from China and Japan were imported to meet the demand.
As the production of sugarcane continued to increase, the Hawaiian Islands underwent significant transformation in order to meet the demands created by the new industry. Island-wide networks of ditches, tunnels, canals and reservoirs were constructed in order to intercept, store and deliver rainfall runoff to the sugarcane fields. The irrigation network was so successful that it enabled cultivation on the leeward side of the islands, which are much drier than the opposite windward side.

The transformation of the local drainage patterns came at significant cost to native Hawaiians, who were powerless to stop the loss of a resource that they depended on for their own agricultural uses. Historically, Hawaiians were self-sufficient, relying for centuries on the cultivation of, among other things, the kalo (Hawaiian for taro) plant. Kalo, similar to sugarcane, requires a large amount of water for cultivation and the production of taro reduced drastically due to the rise of sugarcane farming.

Sugar production in Hawaii has been in decline since the 1970s. Despite having once been the primary economic driver for the state of Hawaii, the final remaining commercial-scale sugar farm ceased operations on December 12, 2016 (Associated Press).

**Project Background**

Ukumehame Reservoirs Nos. 2 & 3 are situated on the southwestern side of Maui, approximately 8 miles southeast of the city of Lahaina (see Figure 1). The reservoirs and the adjacent Ukumehame Ditch were constructed in 1905 (Wadsworth) by the Honolua Ranch & Pioneer Mill Company.

![Figure 1 Island of Maui, HI](image)

The reservoirs are side-by-side, offline reservoirs which are situated within Ukumehame Gulch and immediately adjacent to the main stream channel centerline (see Figure 2), which runs along the southeastern side of the reservoirs and discharges into the Pacific
Ocean approximately 0.8 miles away. The reservoirs were historically filled by directing water from the manmade Auwai Ditch (which runs along the right slope of the Ukumehame Gulch, looking downstream) into the reservoirs by way of a diversion structure.

Due to the existence of a residence immediately downstream of the Reservoir No. 3 embankment and active residential construction between the dams and the ocean outfall from the stream, the reservoirs are classified as high-hazard, meaning that the failure of one or both of the embankments could result in probable loss of human life and significant property damage.

![Figure 2 Project Location Map (imagery source: Google Earth)](image)

The original areas of active sugar cultivation have been abandoned and sold off for residential construction. It is unclear how long the reservoirs were actively in use providing irrigation water to the sugar plantations; however, in recent decades, and with the decline of sugar production on the island, the reservoirs have fallen into disrepair with significant vegetation growing on the embankment slopes and within the reservoir bottoms (see Figure 3).
During an inspection in June 2008, a significant seep was discovered within the Reservoir #3 embankment (see Figure 4). The flow rate was estimated to be 30-50 gpm at the time of measurement (Matsuda) and was clear, indicating embankment material was not being lost at a high rate. As a result of these findings, the State of Hawaii Department of Land and Natural Resources (DLNR) Dam Safety Division required that the level in the reservoirs be immediately lowered and steps be taken to evaluate the severity of the situation out of concern that the seep could develop into a piping failure, and ultimately into a catastrophic loss of the reservoir.

Following the discovery of the seep, Gannett Fleming prepared a Condition Assessment Report in 2009 (Gannett Fleming, Inc.) which included three options for addressing the deficiencies; rehabilitating the structures, converting to a flow-through system as a temporary measure, and breaching the reservoirs. The dam owners chose to pursue a full breach of both of the reservoirs. The embankment between Reservoirs No. 2 and No. 3 would be breached and the embankment between No. 3 and the stream channel would be breached as shown in Figure 5.
The basis for our analysis and design is Hawaii Administrative Rules Chapter 13-190.1. These rules provide design and analysis requirements based on size and hazard classification. Because the Condition Assessment Report included both a rehabilitation and a breach alternative, we evaluated both the PMF and the 100-year floods for this study. The rules state that all high-hazard dams, regardless of height or capacity, shall be
able to pass the full PMF without overtopping the embankments (Hawaii Department of Land and Natural Resources §13-190.1-4(c)). In the event that the reservoirs would have been rehabilitated, this rule would apply. The rules also state that for removal an embankment shall be breached to allow passage of the 100-year flood with a maximum depth of five feet anywhere within the breached channel section (§13-190.1-21(b)(2)); this rule provided the basis for the breach design.

**HYDRAULIC ANALYSIS**

**Model Setup**

We had determined during the hydrologic and hydraulic analyses for the Condition Assessment Report that the PMF within Ukumehame Gulch overtops the embankments and inundates the reservoirs while the 100-year flow remains within the main stream channel. Even though we were proposing to breach the embankments and were therefore only required to evaluate the passage of the 100-year storm event, DLNR Dam Safety requested that we analyze the PMF condition passing through the breaches and determine the maximum depth of flow within the reservoirs. The concern was expressed that the remaining embankments could detain some volume of water, however briefly, which may still pose a risk to the downstream residence.

We determined that an unsteady HEC-RAS model would be necessary to model the various interrelated parts, such as differential timing of the incoming hydrographs, effects due to the storage capacity of the reservoirs, etc. The following model configuration was developed:

- The Ukumehame Gulch is modeled by 34 cross sections cut from a recent survey. All HEC-RAS geometry was cut and exported from Civil 3D 2014.
- The north and east sides of Reservoir 2 are modeled with a lateral weir structure that can exchange flows back and forth with the stream channel.
- The south and east sides of Reservoir 3 are modeled with a separate lateral weir structure that can exchange flows back and forth with the stream channel. This lateral weir reflects the geometry of the proposed breach.
- Reservoirs 2 and 3 are each modeled as storage areas with independent stage-storage relationships.
- Reservoirs 2 and 3 each have directly contributing inflow hydrographs from the previous hydrologic analysis.
- Reservoirs 2 and 3 are connected to each other by way of a storage area connection. The cross section of the storage area connection reflects the proposed breach between Reservoirs 2 and 3.

A schematic of the model and a graphic of the HEC-RAS geometry file are shown in Figure 6 and Figure 7, respectively. It is important to note that the lateral weirs and the storage area connection allow both positive and negative flow. Also, because HEC-RAS calculates the storage areas using level pool routing, there is no time delay between flows entering and leaving a storage area. This is not a significant issue due to the small size of
these reservoirs; however, under different circumstances the travel time within a reservoir may be important to capture.

Figure 6 Unsteady HEC-RAS Connectivity Schematic

Figure 7 Unsteady HEC-RAS Geometry Layout
Analysis of HEC-RAS Output

HEC-RAS provides many good analysis and visualization tools which facilitate quick review and understanding of the model results; these tools can be particularly useful when evaluating an unsteady model. For our purposes with this model, however, we needed to be able to visualize the output in ways HEC-RAS can’t natively do. For example, we wanted to display the water surface elevations at a HEC-RAS cross section within the stream channel and the water surface elevation (WSEL) in the adjacent reservoir at each timestep within the model so that we could evaluate the differential loading on the embankment. To accomplish this, we used Excel to create graphs to visualize custom views of the HEC-RAS model results.

We accomplished this by importing select cross section data and HEC-RAS stage hydrograph data into Excel. By importing the data from each timestep, we were able to create an interactive spreadsheet where we could step through the model. Figure 8 and Figure 9, below, are examples of the graphs we produced. Each graph includes a scroll bar to interactively step through the model results, which are dynamically updated from the HEC-RAS output.

These figures show the WSEL within the stream channel alongside the WSEL within the storage area(s) during the PMF event.

![Figure 8 Visualization of HEC-RAS Cross Section WSEL (left) and Adjacent Storage Area WSEL (right)](image)
Results of the Analysis

As stated above, the concern expressed by Hawaii DLNR was the potential for the remnant embankment to fail during the PMF, and the sudden release of any temporarily-impounded water. The graphical representations shown above indicate that for the majority of the flow event, the WSEL within the stream channel is higher than the WSEL within the reservoirs. This implies that if any failure were to occur, it would more likely be the embankment failing into the reservoirs and not the other way around.

We presented these results to Hawaii DLNR over web conference. We were able to demonstrate that even during the PMF, the depth and volume within the reservoirs does not appear to create a condition where the remnant embankments could fail and release a surge of water into the downstream reach. With the concurrence of Hawaii DLNR, we proceeded to complete the breach design based on the 100-year inflows from the upstream watersheds only.

Comparison to 2D HEC-RAS Model

Following the completion of the design and the then-recent release of HEC-RAS 5.0 with 2D modeling, we created a comparison model. The 2D grid was created from data exported from our Civil 3D design surface, and the inflow hydrographs used in the 1D model are identical to those used within the 2D model. The maximum WSEL within the reservoirs matched within a reasonable level, and the results predicted by the 1D model are reflected within the 2D model. Figure 10 shows a snapshot of the 2D modeling results. This graphic depicts the greater depths within the channel section (darker blue) compared to the depths within the adjacent reservoir.
**Recommendation for Additional Investigation**

The 2D HEC-RAS model has not been advanced beyond the initial comparative analyses described above. In the future, this model can be updated with additional detail such as spatially variable roughness and refinement of the two dimensional grid. While it is not expected for the results to match precisely between the 1D and 2D models, close agreement will lend credibility to the initial one dimensional analysis performed for this project.

**CULTURAL SENSITIVITY**

Immediately to the north of Reservoir No. 2 sits a lo'i, or a kalo patch, which is still being cultivated to this day. This lo'i is accessed by crossing the Reservoir Nos. 2 and 3 embankments and is owned by the family of Ekolu Lindsey, who continues the centuries-old tradition of cultivating kalo.
The existence and maintenance of this lo'i is very important to preserve a part of the Hawaiian heritage. In recognizing this importance, we took additional steps in the preparation of the design and construction documents in order to prevent disturbance of this valuable piece of land, to maintain the water source from the nearby ditch, and to maintain access for the local residents who care for it. These steps may also include informing local community members at a public forum of the planned construction activities and revegetating the disturbed areas with a seed mixture of only native grasses and plants. We are conscious of what can be a delicate situation and want to strike an appropriate balance between the need to remedy the deficient dam and public safety hazard, and the need to preserve Hawaii’s natural resources for those who cherish them.

CONCLUSION

Following the discovery of a dam safety issue at Ukumehame Reservoir Nos. 2 & 3, we were presented with a unique opportunity and challenge. This project required some understanding of the local culture and history, and sensitivity to the needs of DLNR, our client and the local residents.

The analysis of the Ukumehame Reservoirs was a bit atypical; offline reservoirs which nonetheless receive a substantial inflow volume from an adjacent stream. A concern was expressed that, even though the embankments were to be breached, could the capacity of the breached section restrict flows as they pass through the reservoir? And if so, could a failure of the remnant embankments during a flood event release a surge of water and still pose a threat to people or property downstream? In order to understand this situation, an unsteady HEC-RAS model was created which allowed us to understand the how flows within the main stream and reservoirs relate. This allowed us to suggest that a failure of the remnant embankments would likely not release a surge of water downstream because the reservoir WSEL is lower than the adjacent stream WSEL for the majority of the flow duration.
Additionally, this project required sensitivity to other, non-technical issues such as the cultural and historical significance of the project area, and how the proposed modifications to the reservoirs will impact the local residents. For this project to be a success once construction is complete, it will require more than a design which simply addresses the need to breach the reservoirs; it will require reaching out to local residents, educating them about the project, learning about their concerns and preparing into a design which does its best to satisfy the needs of those involved.

ACKNOWLEDGEMENTS

Thank you to Mark Lake for contributing to the project background by coming through on records requests and thank you to Ekolu Lindsey for sharing insights into the cultural importance of the Ukumehame Reservoirs and your personal experiences with the adjacent lo'i.

REFERENCES


