Modeling the Downstream Consequences of the 1976 Teton Dam Failure and Resulting Flood by Validating the GeoClaw Software with Historical Data

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ABSTRACT

Worldwide, geohazards threaten the lives and livelihoods of millions. A low probability but high-risk geohazard with a large manmade component are threats from dam failures. The June 5th, 1976 Teton Dam failure in Eastern Idaho devastated communities downstream and cost 2.9 billion dollars in damage, and the lives of eleven people. Overall, the dam infrastructure in the US is aging and a method to evaluate consequences from these potential geohazards is necessary. Computer simulations present an opportunity to understand these geohazards. The development of a numerical model of the Teton Dam failure was constructed using GeoClaw software package. By combining numerical modeling capabilities of GeoClaw with potential field observations obtained via drone photogrammetry, we characterize the flooding resulting from the dam failure and develop a better understanding of geophysical parameters needed to calibrate our numerical model. We validate arrival times, flooding depth and flood boundaries using historical data and field observations. Field methods focus on recovering detailed terrain coverage to enhance existing digital elevation maps (DEMS). Additionally, we are using Structure for Motion (SfM) generated topography for an informational video depicting flooding events and improving citizen science fluency. Expected results from this study include agreement with historical flooding levels and simulated gauge data, and validation of the GeoClaw software for dam failure modeling. Downstream consequence modeling allows for a better understanding of risks associated with dam failures and will lead to improved floodplain management plans. We are calibrating the GeoClaw software so future dam modeling can be conducted to create

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flood maps for local communities, to communicate threats to lawmakers in a visually impactful way, and to aid in the design and location of future dams.

INTRODUCTION.

Worldwide, geohazard disasters cause societal and economic impacts that threaten the lives of millions. Dams are a geohazard with a large manmade component. Nearly 30% of dams in the United States would risk the loss of human life and significant property damage if they were to fail[(1)]. According to the Association of Civil Engineers, the infrastructure of dams within the United States scores a 'D' average[(2)]. Additionally, over 20% of the dams in the United States are marked for high hazard potential[(2)]. With 840,000 dams in the United States aging every year, there is a need for high resolution simulation modeling of potential dam failures and the resulting downstream consequences[(2)]. In order to improve public safety and community resilience, both the risks of and the consequences associated with dam failure must be lowered, and numerical modeling is a tool to improve dam safety overall.

HISTORIC TETON DAM FAILURE.

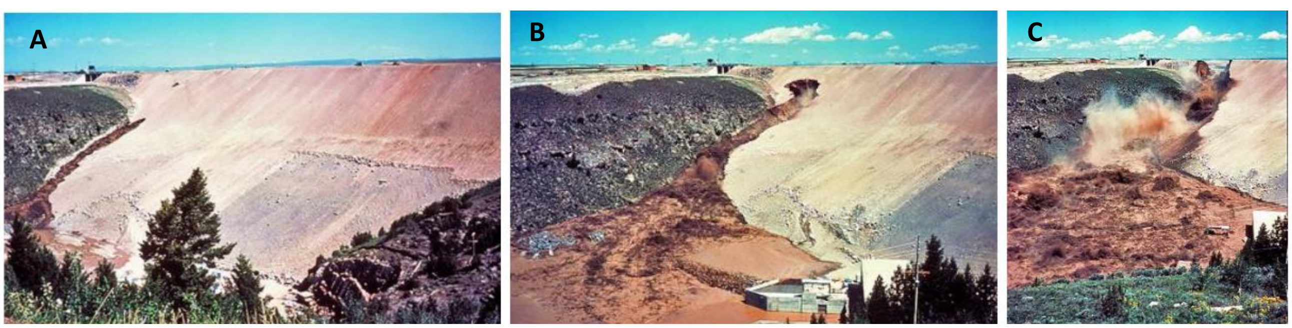

Figure 1. *The historic Teton Dam Failure documented by the Bureau of Reclamation photos occurring at (A) 11:30 AM, (B) 12:00 PM, (C) 12:05 PM [(3)].*

On June 5th, 1976 the earthen Teton Dam in Eastern Idaho failed. 80 billion gallons of reservoir water devastated downstream communities by taking the lives of eleven people and costing over 2.9 billion dollars in damage (8.4 billion in today's dollars) [(4),(5)]. At some points, the inundation levels over Eastern Idaho were 30-feet in depth[(3)]. The failure was well documented by the Bureau of Reclamation and local civilians, allowing for a robust account of the event (*Figure 1)*.

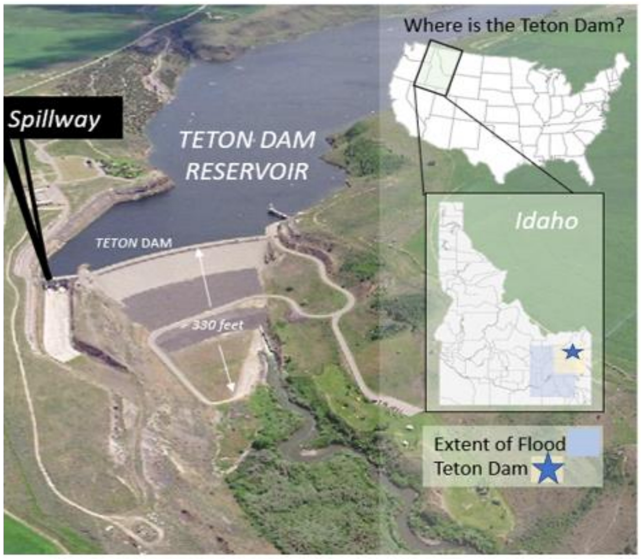

Figure 2. *Location of Teton Dam in Eastern Idaho, with respect to United States early 1976 (amended from Bureau of Reclamation)[3].*

PHYSICAL SITE TETON DAM.

The physical site of the research is the dam break catchment system in Eastern Idaho, United States. The modeled height of the Teton Dam is 305 feet and aligns with the historical height, and the dam was fed by the Teton River, a tributary to the Snake River[3] (*Figure 2*). This dam was chosen because the failure was well documented, and its proximity to Boise, ID.

RESEARCH OBJECTIVES. In this study we aim to:

- Use 2D shallow water model to simulate the Teton Dam failure flooding with evolving free boundary and free surface embedding into a background Cartesian mesh
- Run a high-resolution simulation using dynamically evolving meshes to model the resulting flood, for the full flood duration
- For model validation, use numerical gauges for easy comparison with historical literature values of inundation depths
- Accurately model historic reservoir volume and initial dam break
- Combine geophysical and geological methods with numerical modeling to ensure model validity

METHODS

The methods for this paper are broken down into two phases. Phase 1 involves numerically modeling the Teton Dam flood using GeoClaw. Phase 2 involves a geophysical field expedition to collected drone photogrammetry data and Structure for Motion (SfM). However, in Spring 2020 the planned field work expedition was not possible due to travel restrictions and permitting restrictions. Therefore, this phase will be conducted in Fall 2020.

PHASE 1: NUMERICAL MODELING WITH GEOCLAW

In this research, in order to accurately simulate the Teton Dam flood, a numerical model is developed, based on solving shallow water equations (SWE) on an adaptively refined Cartesian mesh. In this computational model, a robust Reimann solver handles evolving wet and dry fronts. The software also makes it easy to manage multiple overlapping topography files. The implementation of numerical gauges allows for comparison of modeled results to historic inundation depths (*Table 1*).

***Table 1**. Gauges instituted into the GeoClaw model for agreement with historical data. Each gauge has its associated latitude and longitude in the model (darker gray color). The flooding depth, arrival time, and distance from the dam are available in historical records (light gray) [3].*

Gauge Name	Gauge Number	Latitude (deg)	Longitude (deg)	Flooding Depth (ft)	Flood Arrival Time	Miles from the Dam
Teton Canyon	1	-111.5939	43.9341	50	12:05 PM	2.5
Teton Canyon Mouth	2	-111.6664	43.9338	40	12:10 PM	5.0
Wilford	3	-111.6721	43.9144	15	12:45 PM	8.4
Sugar City 1	4	-111.7601	43.8633	15	01:30 PM	12.3
Sugar City 2	5	-111.7434	43.8738	20	01:30 PM	12.0
Rexburg	6	-111.7923	43.8231	6-8	02:30 PM	15.3
Blackfoot	7	-112.3407	43.1876	0.5-1	10:00 AM	112.1

GeoClaw is a depth-averaged code based on the conservative finite volume discretization method and was chosen as the software to model the Teton Dam flood as it overcomes technical challenges other software's are limited by such as using OpenMP parallelism for maximum computational power[7]. This code has been widely used for tsunami modeling and has been validated for use in emergency management scenarios[6].

Several steps are necessary in creating and running the model of the Teton Dam failure in GeoClaw. Two topography files (10 m^2 resolution) were pre-processed, loaded, and identified in the code as boundaries for the simulation (*Figure 3*). Input parameters include simulation resolution, simulation duration,

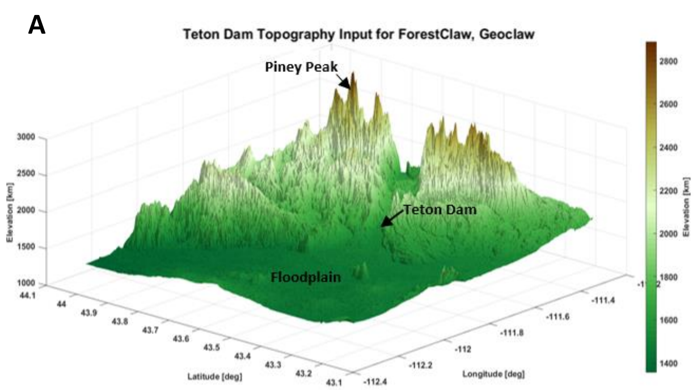

Figure 3. *(A) Topographic inputs for GeoClaw are pre- processed in MATLAB to generate topography for the model runs. This figure (left) demonstrates a vertically exaggerated topography from a USGS DEM file. (B) Gauges above from Table 1.*

location of numerical gauges, and number of output files**.** In GeoClaw, the criteria for local mesh refinement (AMR) was specified(8). In the flooding scenario, we locally refine the mesh to follow the evolving flooded regions. Regions to be refined were installed based initial reservoir levels. Gauges were denotated as regions of refinement and identified using latitude and longitude *(Table 1).* Gauges were used to compare computational results to measurements from historical accounts as a function of time at a fixed geographical position. For visualization, we create a series of output images (.png files) that we overlay onto Google Earth. The color scale on the images is used to depict inundation depth.

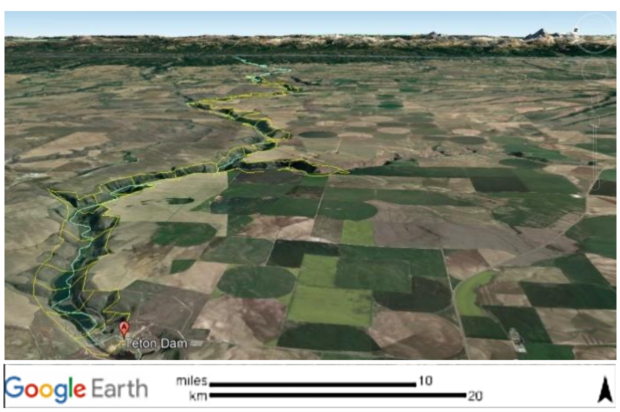

Figure 4. T*he Teton Dam reservoir (17 miles) mapped in Google Earth while determining height (once per mile) and determining total volume within the GeoClaw simulation. The yellow lines are the hypotenuse used to compute the area. © Google, Digital Globe*

Furthermore, the volume of the reservoir was estimated using Google Earth and ArcGIS. Historical sources state the total capacity of the Teton Dam Reservoir was 288,250-acre feet, that the reservoir length was 17 miles in length, and the Teton Dam Canyon from the dam to the canyon mouth was 1,200 feet wide and 5 miles in length(3).Using these parameters, the extent of the Teton Dam reservoir was mapped to calculate the average height and confirm the model's initial volume to be correct. To determine a height for the reservoir, an average height was calculated using Google Earth measurement tools (*Figure 4*). The average height was calculated to be 335 feet (*h)*, the length was 89,760 feet *(l),* and the average width was 825 feet *(w).* The great majority of the reservoir is housed in a large-scale triangular prism. Therefore, the equation for calculating the volume was, $V = \frac{1}{2}whl$. This calculation was accurate generating an average volume of 284,750-acre feet for the model's reservoir, close to the historic value of 288,250-acre feet[(3)].

RESULTS

The ability to measure, predict, and compute downstream consequences of dam failure is of importance in risk assessment and dam hazard mitigation. Until recently, dam failure studies have used of modern HPC software to model initial dam failures but have not focused on downstream consequences and flood mitigation. We compare all historic inundation depths against numerical simulations performed using our GeoClaw numerical dam model. The remainder portion of the results section will focus on the results of three specific gauges: the Teton Dam Canyon gauge, the Rexburg gauge, and the Wilford gauge.

The Teton Dam Canyon gauge showed historical agreement with over 20 feet high waves of inundation moving through the canyon in front of the dam (*Figure 4A*). The initial dam break modeled is depicted on the gauge and shows inundation occurring almost immediately (*Figure 4D*). This gauge shows between 30-40 depth (feet) inundation agreeing with historical values of 40 feet[(3)].

The Wilford gauge largely agreed with historical literature values of inundation, displaying a depth of 15 feet (*Figure 4B*). The land line fluctuations (*Figure 4E, green*) demonstrate the model grid refinement beginning at after 1 hour. The historic dam failure reached Wilford at 12:45 PM. The model shows the flood waters reaching the town at approximately 1:00 PM.

The Rexburg gauge demonstrates inundation agreement with a value of 6 feet (*Figure 4F).* Model grid refinement begins at roughly 1:15 PM. The model registers initial inundation beginning 2:30 PM, in agreement with historical data and the flood waters passing this location at about 6:00 PM.

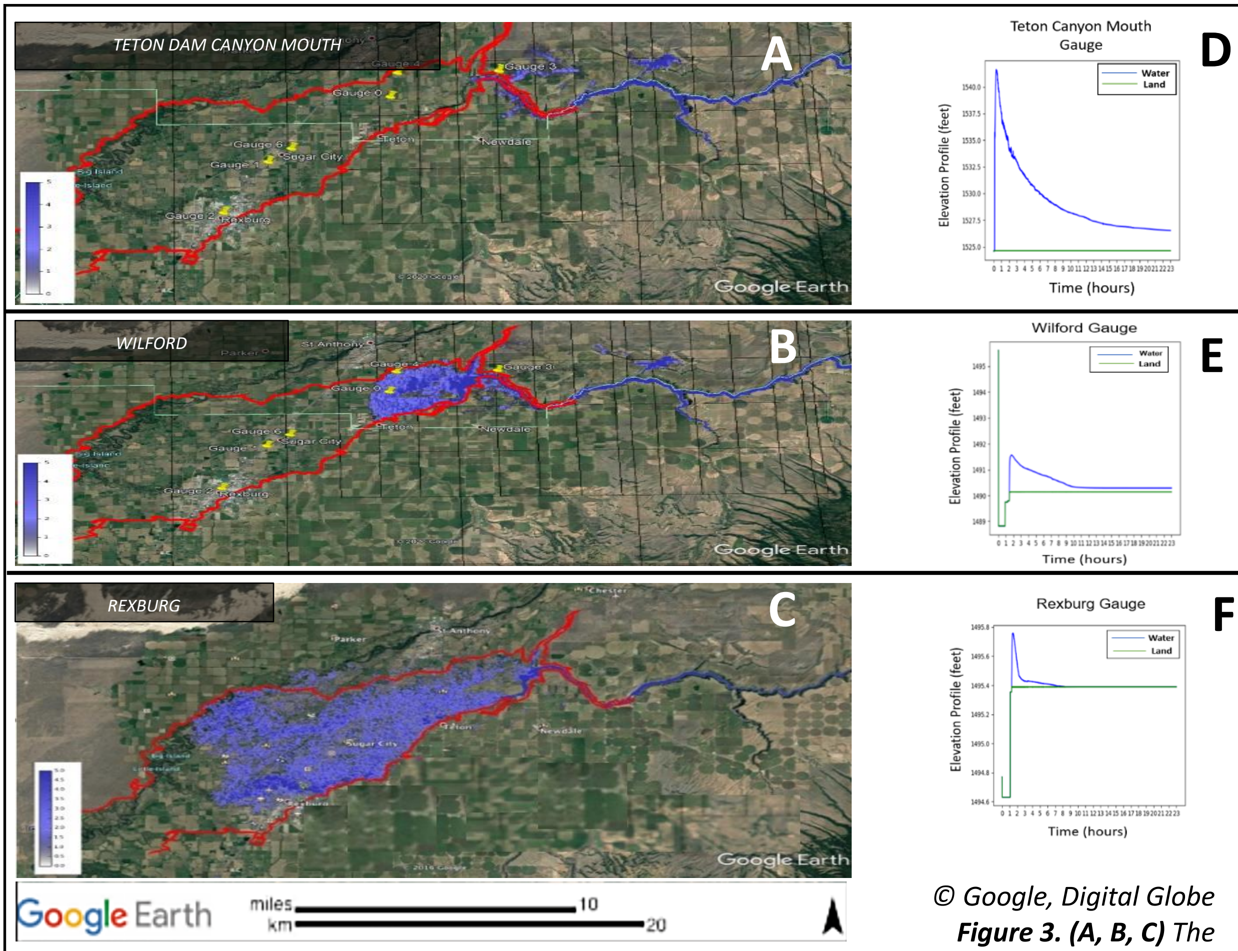

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***Figure 3. (A, B, C)** The floodwater is depicted in shades of blue, and the thicker red line is the digitized flood boundary from historical records (left). **Figure 4. (D, E, F)** The gauges (right) record flood arrival times through the simulation. Within in each gauge, the flood (blue) and the elevation (green) record the inundation height and beginning of topographic refinement sequence.*

DISCUSSION

The catastrophic failure of the Teton Dam in 1976 demonstrated the need for increased numerical modeling and community preparation. The primary goal of this research was to assess the suitability of GeoClaw for simulating the historic failure, and capabilities for matching flood arrival times, the flood's geographic spread, and the inundation height. The preliminary results found that our dam model needs to more accurately capture the initial dam burst to better modulate the waters initial flow and volume.

The Wilford gauge demonstrated flood waters reaching the gauge within 15 minutes of the historical literature value. Within the numerical fidelity of this model, we consider this to be excellent agreement. The Rexburg gauge inundated at 2:30 PM[3] on June 5th, 1976, and our model showed a 2:30 PM arrival time as well, thus the historical literature value aligns very well with our model. Largely, across all seven gauges the inundation levels were found to match historical record and geographic spread, both being compelling indicators that the GeoClaw software can be adapted for dam simulations.

Application of Phase 2 will allow for higher resolution of the dam, and is expected to improve agreement with arrival times, inundation depths, and geographic spread. With further calibration of the GeoClaw software the Teton Dam failure can validate the code. With that validation, we will be able to conduct future dam modeling to create flood maps for local communities, communicate threats to lawmakers in a visually impactful way, and aid in the design and location of future dams.

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