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Predictions on arrival times of water of the St. Francis dam break flood using ANUGA

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Abstract: ANUGA software is used to simulate the 1928 St. Francis dam break flood. ANUGA (see https://anuga.anu.edu.au/) is a free and open source software, which is designed to simulate shallow water flows. Our simulation assessment in this paper is based on the arrival times of water at several stations. We use the BreZo hydrodynamic algorithm results of Begnudelli and Sanders ("Simulation of the St. Francis Dam-Break Flood," *Journal of Engineering Mechanics*, Vol. 133, pp. 1200–1212, 2007) to compare with, in addition to measured arrival times of the real event. Note that in simulations, arrival time can be measured with respect to either the water front or water discharge peak. Our simulations are of two types, catchment and detailed.

The catchment type simulation considers the area extending from the dam site to the Pacific Ocean. It has the dimension 81.3 km by 43 km containing the entire 87 km river reach (about domain diagonal) with around 300,000 triangular computational cells. Our results of the catchment type simulation agree with those of measured arrival times of the real event. These measured arrival times of the real event were investigated by a number of researchers, such as, Outland in 1963 ("Man-made disaster: The story of St. Francis Dam", published by The Arthur H. Clark Company). Note that Begnudelli and Sanders computed arrival times of water at specified stations by checking the arrival of water front and the water momentum (discharge) peak. They obtained that the arrival times of water discharge peaks agree more with measured arrival times of the real event than the arrival times of the water front. However, our ANUGA simulation results in the opposite, that is, arrival times in terms of the water front match better with measured arrival times of the real event.

The detailed type simulation focuses on the upstream reach area. It has the dimension 8.1 km by 6.9 km containing 6 km portion immediately downstream of the dam wall and the 4 km reservoir, making it in total a 10 km (about domain diagonal) model. The aforementioned paper by Begnudelli and Sanders reports on shock waves and sloshing behaviour as the dam break flood wave progressed down the initial portions of the valley. In order to fully investigate these phenomena the detailed ANUGA mesh is set up and includes triangular cells down to the size of 100 m^2. Therefore, we have around 161,000 triangular computational cells for this detailed type simulation. Once again, our computational results indicate that arrival times in terms of the water front match better with measured arrival times of the real event rather than water discharge peaks.

These results confirm that arrival time predictions should be viewed with some scepticism unless modellers have accurate values of computational parameters, such as topography roughness, as Begnudelli and Sanders suggested.

Keywords: *St. Francis dam break, ANUGA software, finite volume, flood inundation*

1. INTRODUCTION

The 1928 St. Francis dam failure in Southern California is relatively well documented. As such it represents an opportunity to validate the accuracy of a flood model. Indeed, this dam break documentation has already been applied to several models. One such model is the BreZo, a two-dimensional finite volume model developed by Sanders (Begnudeli and Sanders, 2007).

Given the availability of this BreZo validation model and data set, it provides for a platform to validate other models. This paper reports on the validation process using the ANUGA model using the St. Francis dam failure scenario. This particular dam break scenario provides for several aspects of validation. Not only is it plausible to validate the models capability to reproduce flood levels but it is also possible to compare hydrographs and even more importantly to some extent the ability of the model to capture the complex flow behaviour identified in the immediate downstream tortuous valley as described by Begnudeli and Sanders (2007). For the present paper, Sanders was approached in order to get access to the same data set as was used in the BreZo model.

ANUGA is a free and open source software developed by The Australian National University (ANU) and Geoscience Australia (GA). Its main developers are Roberts and Nielsen. Its official website is https://anuga.anu.edu.au/. It is designed for simulations of shallow water flows, such as, tsunami and flood inundations. The ANUGA model has some unique features that make it very capable for modelling dam break scenarios. It was designed with the need to properly assess the impact of a fast moving wet-dry interface and resolving extreme shocks. In order to resolve these, a variable size triangular mesh is used instead of a fixed square mesh. The mathematical method underlying ANUGA is a finite volume method for the shallow water equations.

In this paper, two types of simulations are used at different scales. The first type is the entire 87 km river valley which is used to validate timing, hence velocity and hydrographs. The second type is more detailed and presents the 6 km portion immediately downstream of the dam wall, where extreme sloshing and complex reflective shock waves resulted from the massive initial dam break wave. This type also includes the 4 km of reservoir, making it in total a 10 km length. Both types of simulations describe the process of setting up and running a validation of the ANUGA model using data set of the St. Francis dam failure as well as the process required to improve the model results.

The rest of this paper is organised as follows. In Section 2, we provide numerical settings for ANUGA simulations. Results of simulations are presented in Section 3. Finally some concluding remarks are drawn in Section 4.

2. NUMERICAL SETTINGS

As mentioned, the data set has been provided by an author (B. F. Sanders) of a previous validation model. The data is made up of around 65,000 terrain data points of the entire dam reservoir and river reach downstream to the Pacific Ocean, with a higher density of points along the in-stream and out-of-bank area compared to the areas more remote and elevated above the river. The data set has been used to create a Digital Elevation Model (DEM).

We recall the data about the dam and its stored water based on the information given in the paper of Begnudelli and Sanders (2007). The height of the dam was 57 m and the length was 213 m. It contained approximately 47×10^6 m^3 of water. Failure occurred at 23:57:30 local time on 12 March 1928. At that time the reservoir was first filled to its crest. Following this failure, the water travelled about 87 km towards the Pacific Ocean. First it flowed through San Francisquito Canyon (SFC) toward the region which is now Santa Clarita, then through the Santa Clara Valley (SCV) toward Ventura (the Pacific Ocean).

As the initial condition for our model, water is assumed to be at rest in the location of St. Francis Reservoir. Its depth is 559.4 m. Based on this level and the terrain data used by the model, the initial volume of water on the model grid was computed to be 47.1×10^6 m^3. These water depth and volume follow from the data of Begnudelli and Sanders (2007) and Outland (1963).

An important parameter to be specified in the model is the surface roughness. The methodology adopted by Begnudelli and Sanders (2007) involved reviewing the time of arrival of the flood wave as reported by eyewitness accounts and recorded with that reported by the model. Therefore in setting up models with varying grid resolutions, it is likely that the roughness will need to be adjusted to account for the inability to reflect other system losses such as bend losses, etc. Begnudelli and Sanders (2007) reported that the Manning's roughness coefficient they used to simulate the dam break was in the range 0.02 – 0.03. For our

ANUGA simulations, we use a value for the Manning's coefficient of 0.025. Considering that time is recorded in seconds in the ANUGA model, we list the target time of water arrival for the ANUGA model in seconds.

There are several issues worth mentioning here that may influence the outcomes:

- The fact that an event as extreme as a dam break carries with it massive debris and sediment, introduces the possible need to adjust both density and viscosity of the fluid.
- Currently these are not adjustable parameters in ANUGA. The ability to adjust these should be seriously considered in further model development.
- Similarly it is known that areas in the upstream reach (just downstream of the dam) were severely scoured. This introduces the need to be able to adjust the bed terrain to reflect this scour. Although it is currently feasible to adjust the bed terrain in ANUGA, currently there are no algorithms in the code to determine the extent of scour.
- Modelling of the dam break may be made more accurate by accurate determination of the Manning's roughness spatial variation. Note that the roughness is prone to some adjustment during the event due to both scour and the massive change in flow depth.

It should be noted that due to the extreme flow depths it is likely that in fact the best methodology for an analysis would be to adopt a depth varying roughness application procedure. The approach of a non-constant roughness parameter is discussed by Chanson (2006).

Now we provide a description of the two types of simulations:

- The first is the catchment type, that is, the entire 87 km river reach with a rectangular domain 81.3 km by 43 km. This covers around 3500 km^2. The number of triangular computational cells is around 300,000. In order to keep the output file to a reasonable size results have been saved at 180 second time step. This should provide adequate detail for the majority of the reach. The more detailed model which captures the first 3 cross sections will be saved at a 5 second time step.
- The second is the detailed type, that is, the first 10 km length. This covers an area approximately 8.1 km by 6.9 km, that is, an area of around 5580 ha. The mesh generated in this area has around 161,000 triangles. The level of refinement is only evident upon zooming into the area around the dam.

Illustrations of the computational domains for the entire 87 km and the detailed 10 km settings are given in Figures 1 and 2 respectively.

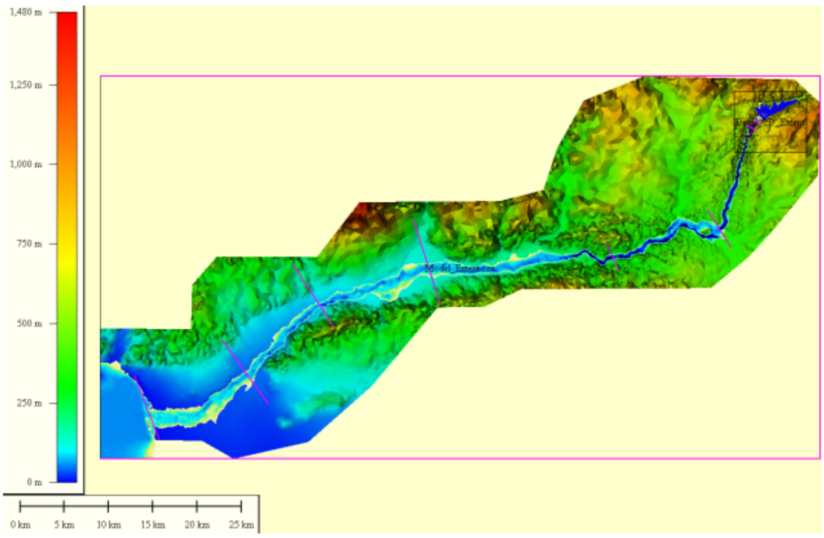

Figure 1. The entire 87 km setting. Straight lines crossing the valley represent specified water stations.

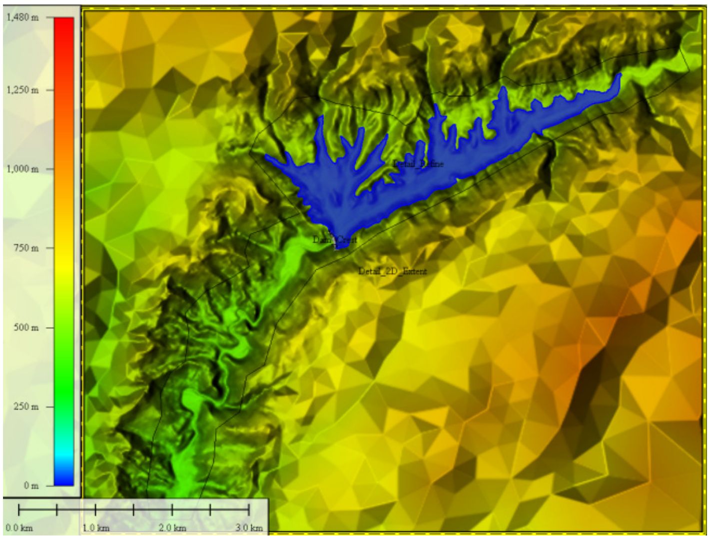

Figure 2. The detailed 10 km setting. This computational mesh is finer than the entire 87 km setting.

3. SIMULATION RESULTS

In this section, we present our simulation results on the predictions of arrival times of water of the St. Francis dam break flood at specified stations. The station positions are listed in Table 1. We recall that BreZo model employed seven positions (XS) of stations, namely, A-A', B-B', C-C', D-D', E-E', F-F' and G-G'. For our work in this paper we consider nine stations, from XS-1 to XS-9, where XS-1 and XS-2 are two additional stations devoted to the detailed type of simulation. Furthermore, XS-3 (A-A') to XS-9 (G-G') are actually the stations used in the BreZo model.

For the entire 87 km simulation, the arrival times of water at the stations are summarized in Table 2. In the BreZo model (Begnudelli and Sanders, 2007) the arrival times of discharge peaks better match with measured arrival times of the real event rather than the arrival times of the water front. Interestingly, our simulation results show that we have the opposite. That is, we obtain that the arrival times of the water front better match with measured arrival times of the real event rather than the arrival times of discharge peaks. We note that these may highly caused by different numerical algorithms, settings, and parameter values. A corresponding hydrograph is shown in Figure 3, which presents the discharge from XS-1 to XS-9 for this detailed 10 km simulation. Here the phenomenon is the same as that of Begnudelli and Sanders in that the discharge decreases gradually from the station near the dam wall to the station near the Ocean. It should be noted that some of the measured arrival times of the real event are considered "approximations" as stated by Begnudelli and Sanders (2007) and Outland (1963).

Table 1. Specified Stations

BreZo stations (XS)	ANUGA stations (XS)	Location
-	1	Dam wall
-	2	Midway to Power house 2
A-A'	3	Power house 2
B-B'	4	Saugus substation
C-C'	5	Edison Camp at Kemp
D-D'	6	Bardsdale Bridge
E-E'	7	Santa Paula Bridge
F-F'	8	Saticoy Bridge
G-G'	9	Ventura (Pacific) Ocean

Table 2. Estimated Arrival Time (in second) of Water for the Entire 87 km Setting

XS	Measured arrival time (real event)	BreZo peak	ANUGA peak	BreZo front	ANUGA front
A-A'	150	360	540	50	180
B-B'	2400	2220	1980	1560	1800
C-C'	4680	4620	4500	3720	3960
D-D'	8400	7980	8460	7500	8100
E-E'	11100	11520	12240	10800	11700
F-F'	14700	14460	15480	13980	14940
G-G'	19500	19200	20700	18360	19800

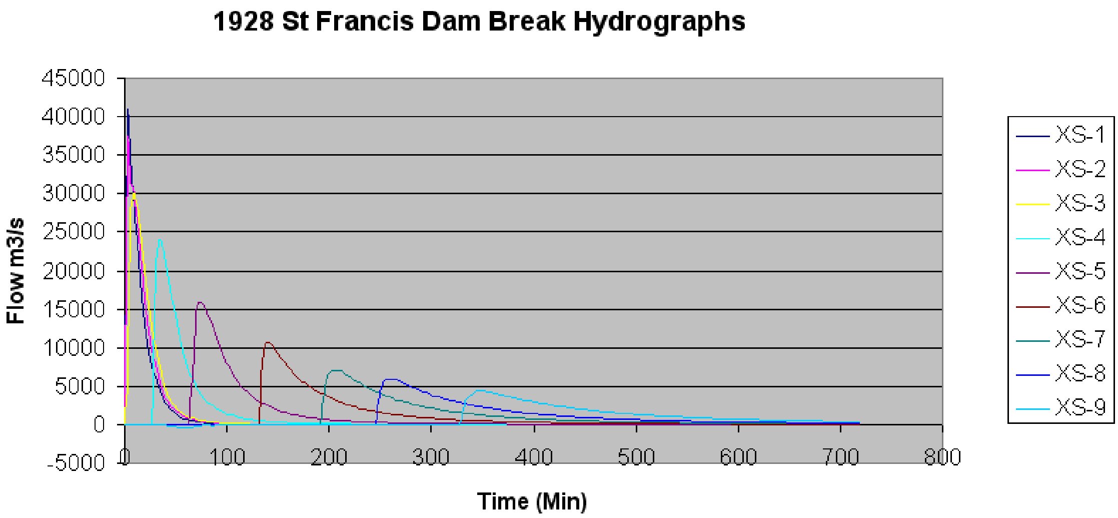

Figure 3. Hydrograph results for the ANUGA entire 87 km setting. XS-1 is the dam wall. XS-2 is the midway to Power house 2. XS-3 is Power house 2. XS-4 is Saugus substation. XS-5 is Edison Camp at Kemp. XS-6 is Bardsdale Bridge. XS-7 is Santa Paula Bridge. XS-8 is Saticoy Bridge. XS-9 is Ventura.

For the detailed 10 km simulation, the water front arrives at cross section A-A (XS-3) at time 140 seconds, which is the arrival time of the water front. The peak of discharge at this cross section A-A (XS-3) is achieved at time 360 seconds. As the measured arrival time of the real event was 150 seconds, it is obvious that again the arrival time of the water front better matches with the measured arrival times of the real event rather than the arrival time of the discharge peak. A corresponding hydrograph is shown in Figure 4, which presents the discharge at XS-1, XS-2, and XS-3 for this detailed 10 km simulation. Again the peak discharges decrease from XS-1 to XS-3, similar behaviour to the hydrograph of the entire 87 km simulation.

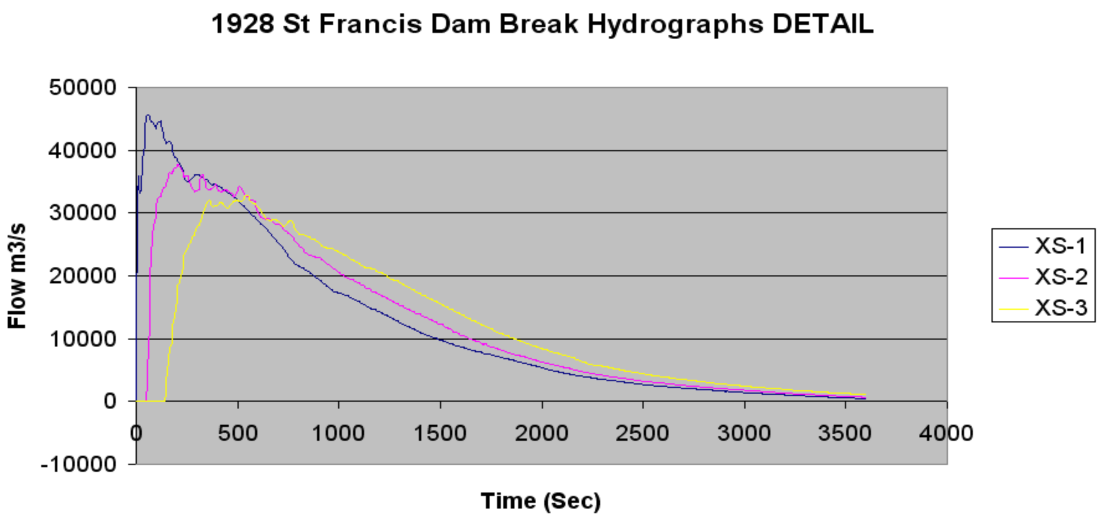

Figure 4. Hydrograph results for the ANUGA detailed 10 km setting. XS-1 is the first station, that is, the dam wall. XS-2 is the midway to Power house 2. XS-3 is Power house 2.

4. CONCLUSIONS

ANUGA software has been used to simulate the 1928 St. Francis dam break. The arrival times of water at specified stations have been investigated in our simulations. Our computational results confirm Begnudelli and Sanders' opinion that arrival time predictions should be viewed with some scepticism. Some modellers can get accurate results of water arrival times based on the water front, while some others can get accurate results of water arrival times based on water discharge peaks. Note that the shallow water equations solved by ANUGA are only an approximate model of fluid flows. However, we could be more confident with our computational results if we had accurate values of computational parameters, such as resistance or roughness coefficient.

For future work, we will implement a depth varying roughness, as suggested by Sanders via personal communication. Inundation map will be investigated based on the depth varying roughness. We will check the sensitivity of results from our algorithm to the mesh resolution in order to confirm the overall robustness of the algorithm.

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