UNCERTAINTY IN DAM BREACH FLOOD ROUTING RESULTS FOR DAM SAFETY RISK ASSESSMENT

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Abstract: Uncertainty in dam breach flood routing results was analyzed in order to provide the basis for the investigation of their effects on the flood damage assessments and dam safety risk assessments. The Monte Carlo simulation based on Latin Hypercube Sampling technique was used to generate random values for two uncertain input parameters (i.e., dam breach parameters and Manning's *n* roughness coefficients) of a dam breach flood routing analysis model. The flood routing results without considering the uncertainty in two input parameters were compared with those with considering the uncertainty. This paper showed that dam breach flood routing results heavily depend on the two uncertain input parameters. This study indicated that the flood damage assessments in the downstream areas can be critical if uncertainty in dam breach flood routing results are considered in a reasonable manner.

Keywords: Uncertainty analysis, Probability risk analysis, Dam safety risk assessment, Dam break analysis, Flood routing analysis, Monte Carlo simulation, Latin Hypercube Sampling technique

1. INTRODUCTION

The main tasks of dam breach routing analysis for dam safety assessment are to route how the dam breach floods would propagate through the valley below the dam and to determine the dam breach flood velocity, arrival time, depth, and boundaries of inundation in the downstream areas. Based on these outcomes from dam breach flood routing analysis, the dam breach flood damages such as economic damage or human life loss are estimated in process of dam safety assessment. Therefore, it is very critical to obtain the exactly calculated results from dam breach flood routing analysis for better dam safety assessment. Current technology permits routing the flood profiles along the downstream when a dam is breached and estimating the characteristics of dam breach flood using the computer models developed for dam breach flood routing analysis. A variety of computer models for dam breach flood routing analysis were introduced, and the computational accuracy and capability of these models have been improved over last decades. However, the results of dam breach flood routing analysis using any computer model are still uncertain due to uncertainty of the input values required for the use of the computer models as well as the imperfection of the computer models. This study was performed to identify the uncertainty in the dam breach flood routing analysis results resulting from the uncertain input parameters rather than the defects of computer models and to clarify the degree of uncertainty in the results predicted by the computer models.

2. STRATEGY FOR UNCERTAINTY ANALYSIS

A number of 1- and 2-dimensional hydraulic/hydrologic dam breach simulation models are available, and they are being used for the practical applications in dam engineering projects. In particular, 1-dimensional hydraulic models such as the National Weather Service (NWS) DAMBRK model (Fread, 1984) are widely being accepted, because they can provide reasonable dam breach flood routing analysis results such as the discharge and stage hydrographs at the given locations downstream of the dam under the dam breach conditions postulated by the model users. This study also employed one of the most advanced 1-dimensional dam breach flood routing analysis models, i.e., the NWS FLDWAV model (NWS, 1998), for the dam breach flood routing analysis. For conducting the uncertainty analysis, this study used a systematic simulation approach, i.e., Monte Carlo simulation, based on Latin Hypercube Sampling (LHS) technique for performing the uncertainty analysis with the NWS FLDWAV. In process of uncertainty analysis using the Monte Carlo simulation, computer programs compiled by Microsoft FORTRAN 4.0 were developed by this study, because the NWS FLDWAV model does not have capability for conducting the uncertainty analysis.

The LHS used in this study is a widely used sampling method in the Monte Carlo simulation method (Iman and Conover, 1980; Loh, 1987; Stein, 1987). The difference between LHS and the simple random sampling used in the standard Monte Carlo simulation method is stratification of the probability distributions for uncertain inputs, wherein n different values are selected from each probability distribution. The values are selected by dividing each probability distribution into n non-overlapping intervals, each of equal probability. Within each interval, one value in each probability distribution is randomly selected. The n values for a uncertain input are then paired in a random manner with the n values of the other uncertain inputs (Palisade Corporation, 1996a). Because the samples from each uncertain input tend to be more evenly spread out over each input distribution, the samples with LHS represent the mean, variance, and other parameters of the output distribution more efficiently (i.e., a small sample size) than with the simple random sampling method. The LHS method, therefore, is usually more efficient and provides better agreement between the sample distribution and the theoretical true distribution (Bohn, Wheeler, and Parry, 1988; Morgan and Henrion, 1990). Further, this method provides better insights into the extremes of the probability distributions of the outputs, because the random samples are generated from all the ranges of possible values.

3. UNCERTAINTY OF INPUT PARAMETERS OF THE NWS FLDWAV MODEL

This study performed the uncertainty analysis for the dam breach flood routing analysis results with respect to the two major uncertain input

Table 1. Guidelines to estimate earth dam breach parameters

Source	Type of dam/condition	Average width (b)	Side slope (z)	Breach time (t_f)
USBR (1989)	Earth dams (well constructed) from table 1 in USBR	$b = 0.5H_d - 3H_d$ where, b = Average breach width, H_d = Dam height	z = Vertical to 1:1 where, z = side slope (H/V)	$t_f = 0.5 - 4$ hr where, t_f = time to fully form the breach
FERC (1991)	Earthen (Engineered, Compacted)	$b = H_d - 5\ H_d$ (Usually $2H_d - 4H_d$)	z = 1/4 - 1	$t_f = 0.1 - 1.0$ hr
Von Thun and Gillette (1990)		$b = 2.5H_w + B$ where , H_w (the height of water above the bottom of the breach) varies with breach type. H_w = full height of the embankment for overtopping / normal maximum water level for other cases. B varies according to	Non-Cohesive Shell Material: H:V=1:1	
		Reservoir Size (ac-ft): B (ft)	Cohesive Shell: H:V=1:1-1:3	Types: Breach formation time
		< 1000: 20		Easily eroded: $0.0046H_w$
		1000 - 5000: 60		Erosion resistant: $0.006H_w + 0.25$
		5000 - 10,000: 140		Easily eroded: $b/(4H_w+200)$
		> 10,000: 180		Erosion resistant: $b/(4H_w)$
Froehlich (1995)		b = 15koVw0.32H0.19 where, b = average breach width (m) ko = 1.4 for overtopping = 1.0 for otherwise Vw = reservoir volume at the time of failure (106m3) H = height of the final breach (m)	z = 1.4, for overtopping = 0.9, for otherwise	$t_f = 3.84V_w^{0.53}H^{-0.90}$ where, t_f = breach formation time is the time needed for complete development of the ultimate breach.
SANCO LD	Earthfill Well Engineered Poorly Engineered	b = 0.5Hd - 3.0Hd b = 1.0Hd - 3.0Hd	z = 0.2 - 2.0 z = 1.0 - 2.0	$t_f = 0.5 - 3.0$ hr $t_f = 0.1 - 0.5$ hr

parameters, i.e., dam breach parameters and Manning roughness coefficients, of the computer models.

3.1 Uncertainty of Dam Breach Parameters

Dam breach parameters required by the NWS FLDWAV model are the dam breach side slope, depth, bottom width, and formation time. The proper values of these dam breach parameters for an existing dam are unknown, even though the dam failure mechanisms are fairly well understood for both embankment and concrete dams. It is because the values for these parameters are strongly affected by the dam type and size, geologic condition of foundation dam, foundation treatment during dam construction, etc (Wahl, 1998). Some guidelines developed by the dam regulatory agencies and researchers, see Table 1, are available to assist in estimating dam breach parameter values, but the estimation of dam breach parameters should not fully depend on the guidelines due to the wide difference of the values recommended by the guidelines. In general, the values of dam breach parameters are subjectively determined based on the values predicted from the guidelines, historical dam failure data, and the dam conditions such as embankment size, materials, and foundation. Thus, some degrees of uncertainty are unwillingly included in process of determining the values of the dam breach parameters and may bring out the errors of flood prediction by the NWS FLDWAV model.

3.2 Uncertainty of Manning's Roughness Coefficients

Roughness coefficient, *n*, used to calculate frictional losses by channel resistance to flow in natural rivers is the variable in Manning's equation that represents river-bed hydraulic roughness (Kung and Yang, 1993). The value of the coefficient is unknown and direct field measurement of the coefficient values is impossible, because the coefficient values are a function of spatial geometry, bed materials, vegetation, flow properties, and other physical parameters. Even though the coefficient values cannot be obtained directly, however, the coefficient values for precipitation floods are generally estimated based on field observations and calibration of observed high water marks from historical flood events. Unlike precipitation floods, the unprecedented magnitude floods such as dam breach flood make it impossible to fully calibrate Manning's roughness coefficient based on previous flood data due to the different characteristics of dam breach floods with precipitation floods. In addition, there are no typical ways to estimate the coefficient values for dam breach floods, so that some degrees of uncertainty are included in the coefficient values estimated using the highest water marks of historical flood events or calibration.

4. CASE STUDY

The computer programs developed for conducting the uncertainty analysis against the dam breach flood routing analysis results were applied to the Alamo Dam located in the west central Arizona. Most of the drainage area of 4770 square miles is bounded by mountainous areas. Alamo Dam was constructed as a multipurpose dam to serve flood control, water conservation and supply and recreation. It was completed in 1964 and constructed as an earth embankment structure 283 ft tall and 975 ft wide. The top elevation of the dam is 1265 ft, and the elevation of the spillway crest is 1235 ft (USACE, 1986).

Alamo Dam breach flood routing analysis and uncertainty analysis for the analysis results were performed against 13 Alamo Dam breach scenarios. They consist of four flood no-failure cases (i.e., ETFN, EPFN, and EPSN), three flood failure cases (i.e., ETFF, EPFF, and EPSF), and three sunny day failure cases (i.e., ESFA, ESFB, and ESFC) under the existing dam condition and four risk reduction cases (i.e., FR2B, FR3C, FR9, and FR12B). The effects of two

Table 2. Dam breach model running scenarios for Alamo Dam risk assessment

Code	Initiating event	Breach run code	Failure/ No failure	Inflow flood	WSE @ breach
Existing(E)	Sunny day Failure (S)	ESFA	Failure (F)	No Flood	1125 ft - earthquake failure (a, Normal operating target elevation)
		ESFB	Failure (F)	No Flood	1207.4 ft - internal failure (b, Historical height)
		ESFC	Failure (F)	No Flood	1235 ft - internal failure (c, Spillway crest)
	Threshold Flood (TF)	ETFN	No Failure (N)	Threshold flood (USACE definition: flood which peaks at dam crest minus freeboard)	N/A
		ETFF	Failure (F)	Threshold flood	1259.6 ft (Max. design surcharge WSE)
	PMP Flood (PF)	EPFN	No Failure (N)	PMF Flood (with starting WSE = 1125 ft)	N/A(Max. WSE during reservoir routing = 1267.67 ft)
		EPFF	Failure (F)	PMF Flood (with starting WSE = 1125 ft)	Dam crest + 1 ft = 1266 ft (Rising limb failure)
	SPF + PMF	EPSN	No Failure (N)	SPF + PMF (with starting WSE = 1180 ft)	N/A
		EPSF	Failure (F)	SPF + PMF (with starting WSE = 1180 ft)	Dam crest + 1 ft = 1266 ft (Rising limb failure)
FR2B	SPF + PMF	FR2B-PSN	No Failure (N)	SPF + PMF (with starting WSE = 1180 ft)	N/A
FR3C		FR3C-PSN	No Failure (N)	SPF + PMF (with starting WSE = 1180 ft)	N/A
FR9		FR9-PSN	No Failure (N)	SPF + PMF (with starting WSE = 1180 ft)	N/A
FR12		FR12-PSF	Failure (F)	SPF + PMF (with starting WSE = 1180 ft)	Dam crest + 1 ft = 1275 ft (Rising limb failure)

Table 3. Descriptions of flood risk reduction alternatives

Code	Description
FR2B	Widen the existing spillway 330 ft, maintaining the existing spillway elevation + raise embankment 10.9 ft
FR3C	Lower the existing spillway 30ft. The spillway was assumed to have a 1h to 4v side slope cut and corresponding spillway lengths were 95ft + raise embankment 11.9 ft
FR9	Combination of lowering the spillway 10 ft and widening 220 ft + raise embankment 10.5 ft
FR12	Raise the embankment to 1274 ft NGVD (Dam crest elevation + raise embankment 9.0 ft), and design for the PMF flood event-Partial fix.

most uncertain input parameters (i.e., breach parameters and Manning's roughness coefficients) on the predicted flood routing results were investigated by this study for the 13 scenarios. Detailed information for dam breach modeling running against these scenarios is summarized in Table 2, and the descriptions of four alternatives are given in Table 3.

4.1 Determination of Uncertainty in Dam Breach Parameters

Among the dam breach parameters necessary for running the NWS FLDWAV model, the values of breach depth and breach bottom width were treated as deterministic in the Alamo Dam case study, because Alamo Dam is an earth dam and its embankment consists of the materials that can easily eroded away by dam breach flood. With consideration of these characteristics of Alamo Dam, the values of breach depth and breach bottom width were determined on the assumption that the breach depth reaches to the bottom of the embankment and the breach bottom width is fully extended to the ends of both side of the valley, see Figure 1, if Alamo Dam is breached by any reason. 275 ft and 100 ft were used as the value of dam breach depth and width for all of Alamo Dam breach model running scenarios, respectively. However, the breach side slope and breach formation time were regarded as uncertain in this case study. To define the values of two uncertain breach parameters regarding seven Alamo Dam failure scenarios (i.e., ESFA, ESFB, ESFC, ETFF, EPFF, EPSF, and FR9), the guidelines in Table 1 were used, and the values recommended by the guidelines are summarized in Table 4. The values of two breach parameters for six no-failure scenarios (i.e., ETFN, EPFN, EPSN, FR2B, and FR3C) were not calculated, because they are not affected by uncertainty in the dam breach parameters. Due to wide differences of the calculated values in Table 4, they were used as reference values for determining the values of two breach parameters for seven failure scenarios. In addition, with considering the characteristics of Alamo Dam and breach conditions, this study assumed that the embankment of Alamo Dam is

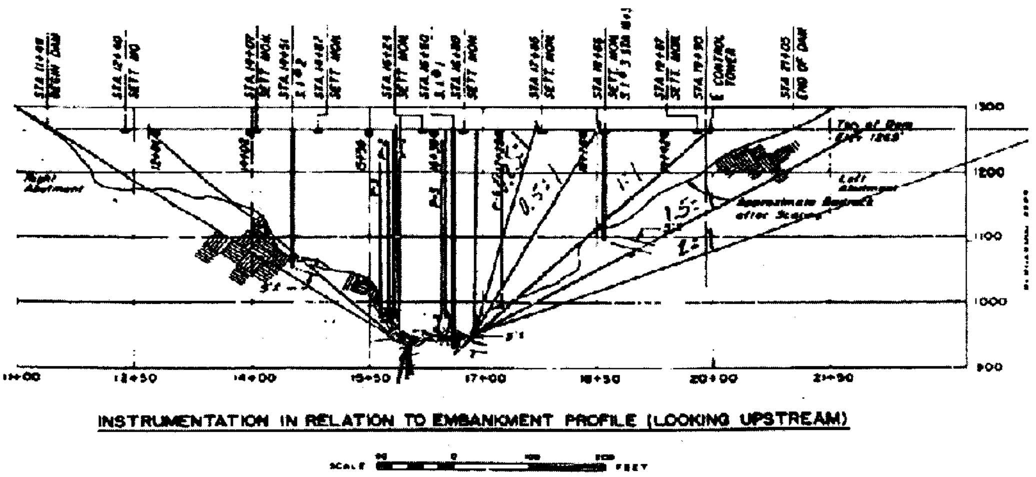


Figure 1. Longitudinal Profile of Alamo Dam
(Source from: Alamo Dam Supplemental Reconnaissance Report, USACE, 1993)

partially breached under the earthquake failure case, partially and fully breached under the internal failure cases, and fully breached under the flood failure cases. Based on these assumption and the recommended values in Table 4, the lower, best estimate, and upper values for the breach side slope and time were determined. In particular, the value of breach side slope for full breaching was directly measured from the profile of Alamo Dam in Figure 1. Furthermore, the breach time of Teton Dam, i.e., 1.25 hour, was considered when the breach time for Alamo Dam was estimated, because Teton Dam has not only the same dam type with Alamo Dam, but also a similar dam size. The probability distributions for two breach parameters were selected among the simple distributions such as uniform, triangular, or normal distributions, because the appropriate probability distribution types to two breach parameters are unknown. In this study, a triangular distribution was used for the breach parameters, and the lower, best estimate, and upper bound values were used as the minimum, mode, and maximum values in the distribution, respectively. Table 5 shows the estimated lower, best estimate, and upper bounds as well as probability distributions for two uncertain breach parameters.

4.2 Determination of Uncertainty in Manning's Coefficients

Due to the different characteristics of the dam breach floods with normal floods such as precipitation floods, the Manning's roughness coefficient values estimated for dam breach flood routing analysis based on historic flood information must be adjusted to account for additional energy losses associated with the dam breach flood (Jarrett, 1984, USGS, 1989). However, the proper amount of adjustment for the coefficients is unknown. Kung and Yang (1993) used +/- 20% as the amount of adjustment for the coefficients based on the dam breach simulation experience for Teton Dam and Buffalo Creek Dam failure and engineering judgment in their study. This study used the same amount of adjustment adopted by Kung and Yang to investigate the impacts of uncertainty in Manning roughness coefficients. The coefficient values used for the deterministic model running for Alamo Dam breach routing analysis were given as the best estimate values and +/- 20% adjusted values of the best estimates were assigned to the upper and lower bounds. A triangular distribution was used to represent the uncertainty in the Manning's coefficient.

4.3. Determination of the Number of Model Running

A variety number of input data sets are produced with the randomly generated values for the uncertain input parameters, when the Monte Carlo simulation technique used for uncertainty analysis. The model runs are made as many as the randomly generated number of input data sets during the Monte Carlo simulation, the same number of model outputs is obtained when the simulation is completed. Therefore, to obtain better statistical information on uncertainty in the model outputs, a large number of randomly generated input data sets are necessary. In the Monte Carlo simulation, it is true that more stable analysis results can be obtained by increasing the number of randomly generated input data sets. However, for a large number of model running, huge amount of simulation time and computational resources are required. Therefore, this study employed the stratified

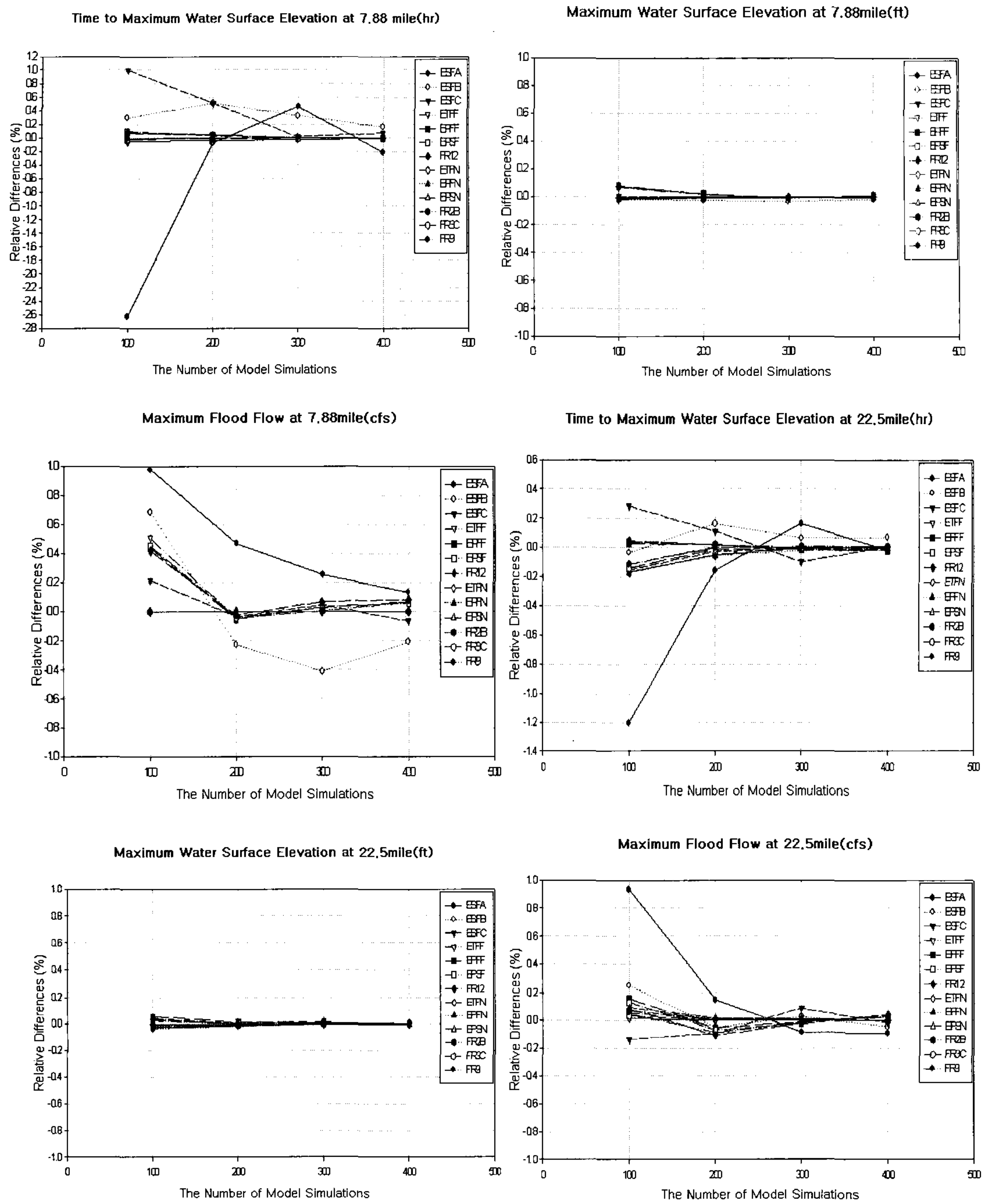


Figure 2. Relative differences of the mean values at 7.88 and 22.5 mile

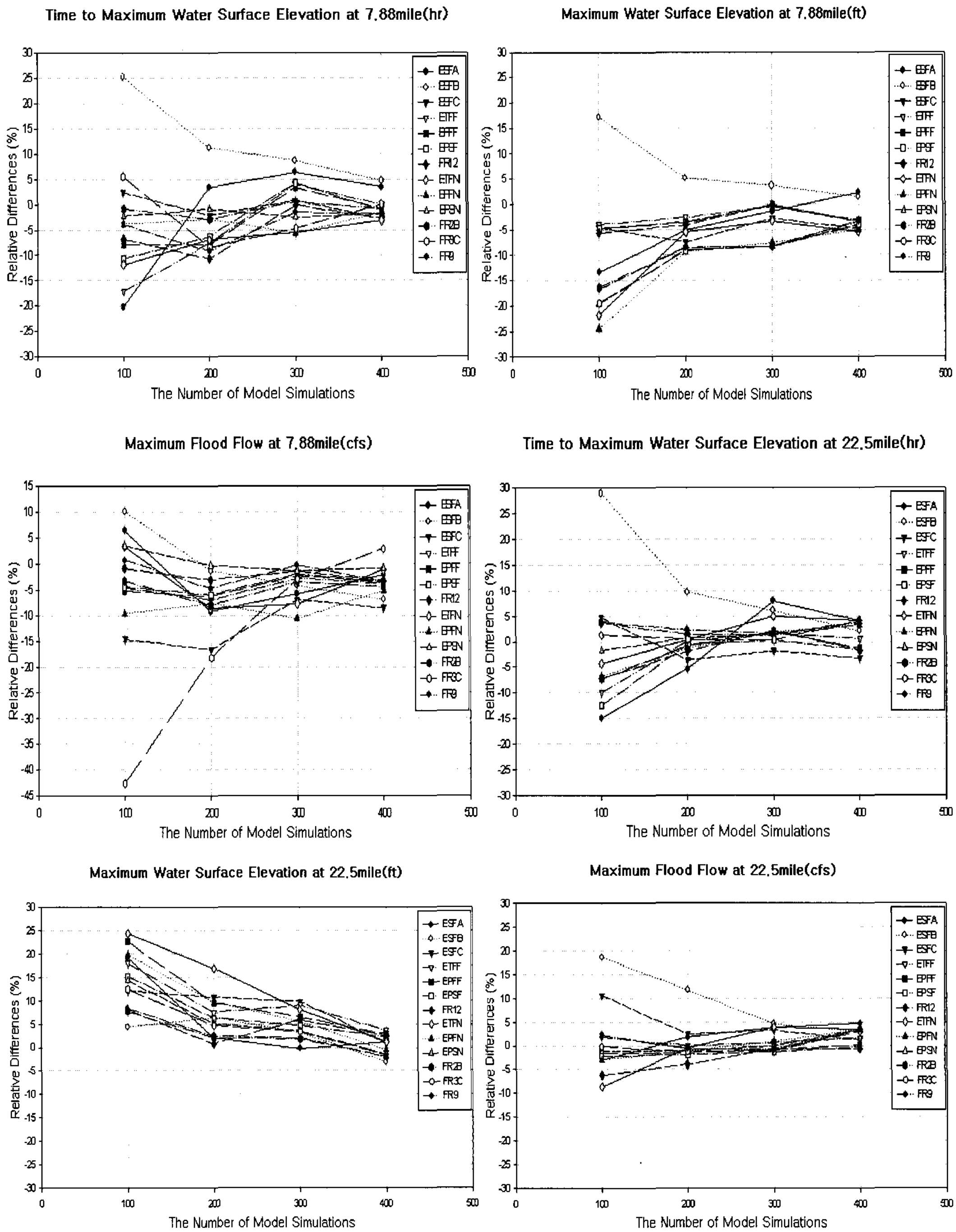
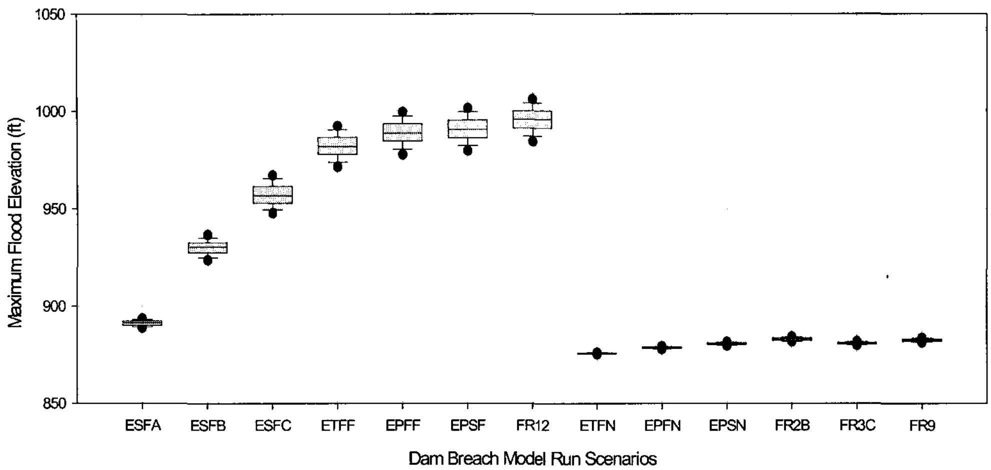


Figure 3. Relative differences of the variance values at 7.88 and 22.5 mile

Table 4. Estimates from the guidelines for dam breach parameters

Failure Scenario	Breach Parameters	Froehlich	FERC	USBR	Von Thun and Gillette	SANCOLD
Sunny Day Failure @ 1125 feet	Breach Formation Time (Hours)	0.8	0.1 to 1.0	0.5 to 4.0	0.685 to 1.330	0.5 to 3.0
(Earthquake failure, i.e., ESFA)	Side Slope (H/V)	0.9	0.25 to 1.0	0.0 to 1.0	0.33 to 1.0	0.2 to 2.0
	Min. Top Breach Width	818.3	720.0	160.0	736	224.0
	Max. Top Breach Width	818.3	1600.0	1280.0	950.0	1600.0
	Min. Bottom Breach Width	242.3	320.0	-160.0	310.0	-480.0
	Max. Bottom Breach Width	242.3	1200.0	960.0	524.4	896.0
Sunny Day Failure @ 1207.4 feet	Breach Formation Time (Hours)	1.8	0.1 to 1.0	0.5 to 4.0	0.669 to 1.824	0.5 to 3.0
(Internal failure, i.e., ESFB)	Side Slope (H/V)	0.9	0.25 to 1.0	0.0 to 1.0	0.33 to 1.0	0.2 to 2.0
	Min. Top Breach Width	1194.1	720.0	160.0	942	224.0
	Max. Top Breach Width	1194.1	1600.0	1280.0	1156.0	1600.0
	Min. Bottom Breach Width	618.1	320.0	-160.0	516.0	-480.0
	Max. Bottom Breach Width	618.1	1200.0	960.0	730.4	896.0
Sunny Day Failure @ 1235 feet	Breach Formation Time (Hours)	2.5	0.1 to 1.0	0.5 to 4.0	0.665 to 1.990	0.5 to 3.0
(Internal failure, i.e., ESFC)	Side Slope (H/V)	0.9	0.25 to 1.0	0.0 to 1.0	0.33 to 1.0	0.2 to 2.0
	Min. Top Breach Width	1373.0	720.0	160.0	1011	224.0
	Max. Top Breach Width	1373.0	1600.0	1280.0	1225.0	1600.0
	Min. Bottom Breach Width	797.0	320.0	-160.0	585.0	-480.0
	Max. Bottom Breach Width	797.0	1200.0	960.0	799.4	896.0
Threshold Failure @ 1259.6 feet	Breach Formation Time (Hours)	3.0	0.1 to 1.0	0.5 to 4.0	0.663 to 2.138	0.5 to 3.0
(i.e., ETFF)	Side Slope (H/V)	0.9	0.25 to 1.0	0.0 to 1.0	0.33 to 1.0	0.2 to 2.0
	Min. Top Breach Width	1504.5	720.0	160.0	1072	224.0
	Max. Top Breach Width	1504.5	1600.0	1280.0	1286.5	1600.0
	Min. Bottom Breach Width	928.5	320.0	-160.0	646.5	-480.0
	Max. Bottom Breach Width	928.5	1200.0	960.0	860.9	896.0
Overtopping Failure @ 1266 feet	Breach Formation Time (Hours)	3.1	0.1 to 1.0	0.5 to 4.0	0.662 to 2.170	0.5 to 3.0
(i.e., EPFF and EPSF)	Side Slope (H/V)	1.4	0.25 to 1.0	0.0 to 1.0	0.33 to 1.0	0.2 to 2.0
	Min. Top Breach Width	2194.2	720.0	160.0	1086	224.0
	Max. Top Breach Width	2194.2	1600.0	1280.0	1300.0	1600.0
	Min. Bottom Breach Width	1298.2	320.0	-160.0	660.0	-480.0
	Max. Bottom Breach Width	1298.2	1200.0	960.0	874.4	896.0
Overtopping Failure @ 1275 feet	Breach Formation Time (Hours)	3.3	0.1 to 1.0	0.5 to 4.0	0.661 to 2.224	0.5 to 3.0
(i.e., FR12)	Side Slope (H/V)	1.4	0.25 to 1.0	0.0 to 1.0	0.33 to 1.0	0.2 to 2.0
	Min. Top Breach Width	2305.1	740.3	164.5	1111	230.3
	Max. Top Breach Width	2305.1	1645.0	1316.0	1331.5	1645.0
	Min. Bottom Breach Width	1383.9	329.0	-164.5	673.5	-493.5
	Max. Bottom Breach Width	1383.9	1233.8	987.0	893.9	921.2



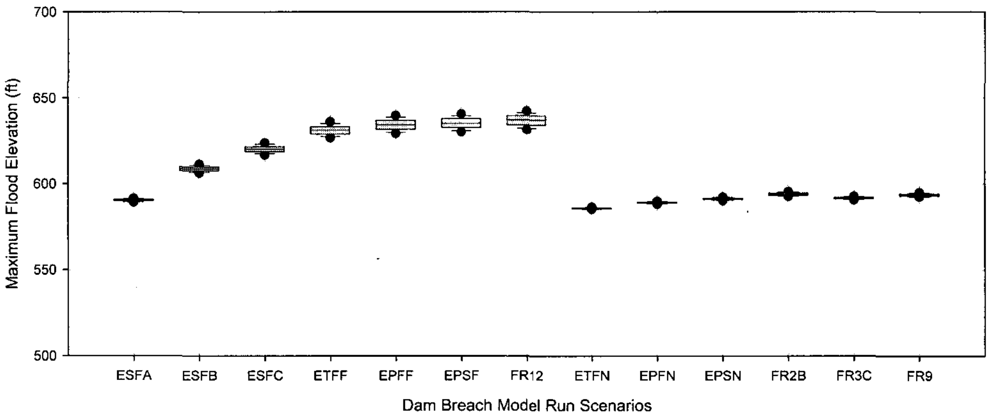
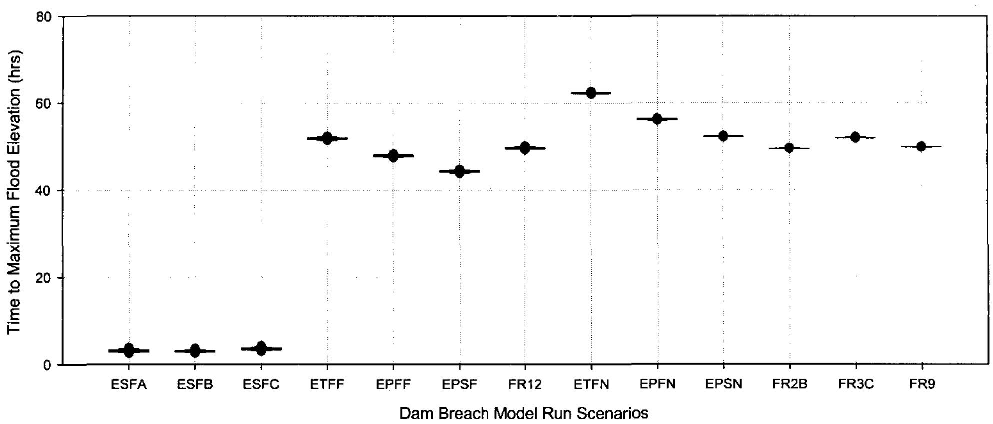


Figure 4. Boxplots for maximum flood elevation at 7.88 and 22.5 mile



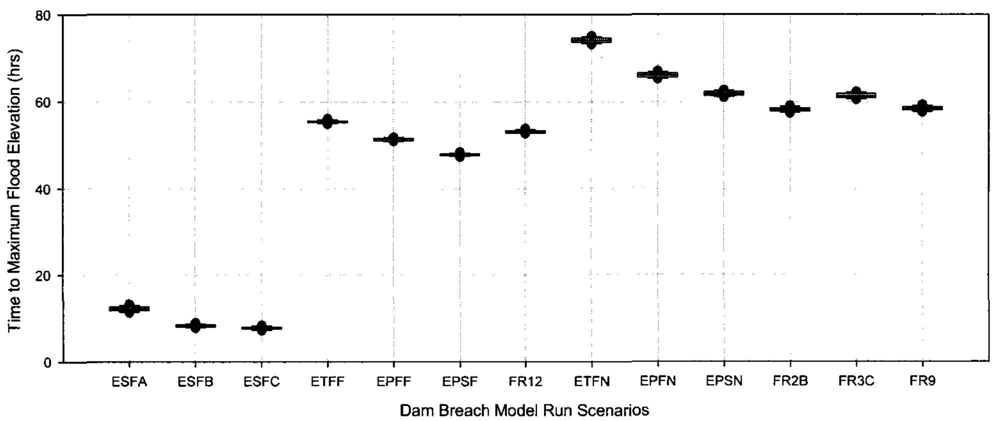


Figure 5. Boxplots for time to maximum flood elevation at 7.88 and 22.5 mile

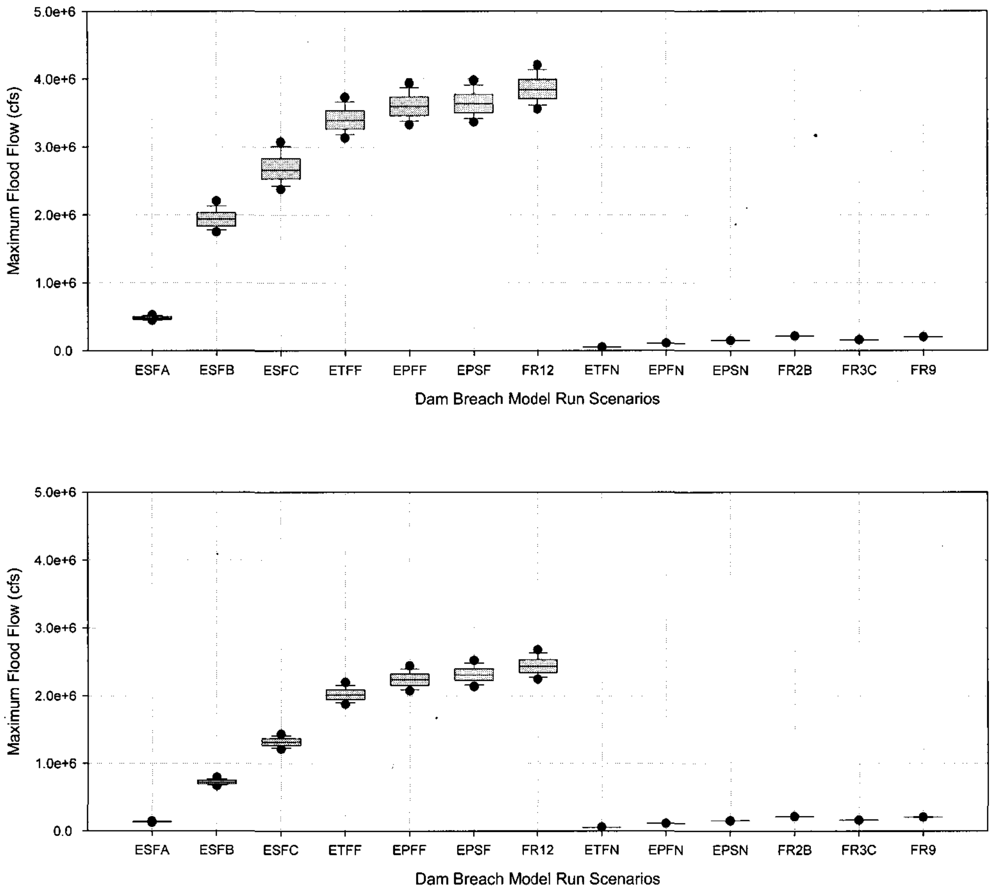


Figure 6. Boxplots for maximum flood flow at 7.88 and 22.5 mile

Table 5. Breach parameters and distribution types for Alamo Dam

Breach Parameters	Breach Side Slope (H/V)				Breach Formation Time (hour)			
Failure Cases	Lower	Best estimate	Upper	Distribution	Lower	Best estimate	Upper	Distribution
Earthquake (Res. Elev. 1125ft)	0.25	0.625	1.00	Triangular	0.75	1.50	3.00	Triangular
Internal Failure (Res. Elev. 1207.4ft)	0.50	0.750	1.34	Triangular	0.75	1.25	2.00	Triangular
Internal Failure (Res. Elev. 1235ft)	0.50	1.000	1.34	Triangular	0.75	1.25	2.00	Triangular
Flood Failure	1.34	1.34	1.34	Triangular	0.75	1.25	2.00	Triangular

Table 6. Statistics for maximum flood elevation at 7.88 mile

Statistics	7.88 mile												
	Failure Cases							No-Failure Cases					
	ESFA	ESFB	ESFC	ETFF	EPFF	EPSF	FR12	ETFN	EPFN	EPSN	FR2B	FR3C	FR9
Deterministic value	8.91E+02	9.29E+02	9.57E+02	9.83E+02	9.89E+02	9.91E+02	9.96E+02	8.76E+02	8.79E+02	8.81E+02	8.83E+02	8.81E+02	8.83E+02
Mean	8.91E+02	9.30E+02	9.57E+02	9.82E+02	9.89E+02	9.91E+02	9.95E+02	8.76E+02	8.79E+02	8.81E+02	8.83E+02	8.81E+02	8.82E+02
Median	8.91E+02	9.30E+02	9.57E+02	9.82E+02	9.89E+02	9.91E+02	9.96E+02	8.76E+02	8.79E+02	8.81E+02	8.83E+02	8.81E+02	8.83E+02
Maximum	8.95E+02	9.51E+02	9.77E+02	9.98E+02	1.01E+03	1.01E+03	1.01E+03	8.76E+02	8.80E+02	8.82E+02	8.84E+02	8.82E+02	8.84E+02
Minimum	8.88E+02	9.19E+02	9.44E+02	9.65E+02	9.71E+02	9.73E+02	9.78E+02	8.75E+02	8.78E+02	8.79E+02	8.81E+02	8.80E+02	8.81E+02
Variance	2.13E+00	1.63E+01	3.58E+01	3.96E+01	4.08E+01	4.11E+01	4.05E+01	7.15E-02	1.94E-01	3.63E-01	6.25E-01	3.82E-01	5.68E-01
Skewness	3.55E-02	3.77E-01	2.19E-01	-3.03E-02	-5.52E-02	-6.05E-02	-6.25E-02	-9.88E-03	-2.50E-02	-2.04E-02	-5.02E-02	-1.99E-02	-4.66E-02
Kurtosis	-7.59E-01	1.12E+00	-2.89E-01	-4.73E-01	-4.20E-01	-4.02E-01	-3.66E-01	-7.75E-01	-9.68E-01	-1.15E+00	-1.19E+00	-1.16E+00	-1.19E+00
Percentile of deterministic value	51.60%	39.60%	50.80%	55.60%	54.00%	53.60%	55.80%	49.80%	49.60%	50.00%	49.80%	50.00%	49.80%

Table 7. Statistics for maximum flood elevation at 22.5 mile

Statistics	22.5 mile												
	Failure Cases							No-Failure Cases					
	ESFA	ESFB	ESFC	ETFF	EPFF	EPSF	FR12	ETFN	EPFN	EPSN	FR2B	FR3C	FR9
Deterministic value	5.90E+02	6.09E+02	6.20E+02	6.31E+02	6.34E+02	6.35E+02	6.37E+02	5.86E+02	5.89E+02	5.91E+02	5.94E+02	5.92E+02	5.94E+02
Mean	5.90E+02	6.09E+02	6.20E+02	6.31E+02	6.34E+02	6.35E+02	6.37E+02	5.86E+02	5.89E+02	5.91E+02	5.94E+02	5.92E+02	5.94E+02
Median	5.90E+02	6.09E+02	6.20E+02	6.31E+02	6.34E+02	6.35E+02	6.37E+02	5.86E+02	5.89E+02	5.91E+02	5.94E+02	5.91E+02	5.94E+02
Maximum	5.92E+02	6.13E+02	6.26E+02	6.42E+02	6.45E+02	6.44E+02	6.51E+02	5.86E+02	5.90E+02	5.92E+02	5.96E+02	5.93E+02	5.95E+02
Minimum	5.89E+02	6.05E+02	6.15E+02	6.24E+02	6.27E+02	6.28E+02	6.29E+02	5.85E+02	5.88E+02	5.90E+02	5.92E+02	5.90E+02	5.92E+02
Variance	4.57E-01	2.49E+00	4.32E+00	8.81E+00	1.04E+01	1.06E+01	1.17E+01	9.57E-02	2.36E-01	4.19E-01	8.30E-01	4.59E-01	7.58E-01
Skewness	1.04E-01	-2.03E-02	9.76E-02	1.83E-01	8.18E-02	-5.19E-04	7.38E-02	-8.97E-03	1.46E-02	2.17E-02	4.33E-02	2.97E-02	4.26E-02
Kurtosis	-2.67E-01	-6.67E-01	-3.50E-01	-4.34E-01	-6.83E-01	-8.49E-01	-4.02E-01	-8.41E-01	-6.39E-01	-8.04E-01	-1.07E+00	-8.61E-01	-1.05E+00
Percentile of deterministic value	52.20%	48.60%	49.60%	52.40%	52.20%	51.80%	53.60%	51.60%	52.40%	51.00%	50.40%	50.80%	49.20%

Table 8. Statistics for time to maximum flood elevation at 7.88 mile

Statistics	7.88 mile												
	Failure Cases							No-Failure Cases					
	ESFA	ESFB	ESFC	ETFF	EPFF	EPSF	FR12	ETFN	EPFN	EPSN	FR2B	FR3C	FR9
Deterministic value	2.90E+00	2.90E+00	3.50E+00	5.18E+01	4.77E+01	4.42E-01	4.97E+01	6.23E+01	5.62E+01	5.22E+01	4.95E+01	5.20E-01	4.99E+01
Mean	3.13E+00	3.02E+00	3.60E+00	5.18E+01	4.77E+01	4.42E-01	4.97E+01	6.22E+01	5.62E+01	5.22E+01	4.95E+01	5.20E-01	4.99E+01
Median	3.10E+00	3.00E+00	3.60E+00	5.18E+01	4.78E+01	4.42E-01	4.96E+01	6.22E+01	5.62E+01	5.22E+01	4.95E+01	5.20E-01	4.99E+01
Maximum	4.10E+00	3.80E+00	4.50E+00	5.24E+01	4.84E+01	4.50E-01	5.04E+01	6.27E+01	5.65E+01	5.24E+01	4.96E+01	5.21E-01	5.00E+01
Minimum	2.20E+00	2.30E+00	2.60E+00	5.10E+01	4.68E+01	4.34E-01	4.88E+01	6.18E+01	5.58E+01	5.21E+01	4.94E+01	5.18E-01	4.97E+01
Variance	1.48E-01	7.92E-02	1.09E-01	6.51E-02	6.70E-02	6.92E-02	6.81E-02	2.73E-02	3.29E-02	4.76E-03	3.67E-03	4.81E-03	3.09E-03
Skewness	2.27E-01	4.65E-01	7.79E-02	1.61E-04	2.84E-02	-1.87E-02	5.57E-02	1.38E-01	-1.53E-01	-3.34E-01	8.70E-02	-9.93E-02	1.06E-01
Kurtosis	-6.08E-01	2.65E-01	5.30E-03	-8.92E-02	-1.49E-01	-9.92E-02	-1.46E-01	-5.23E-01	-9.97E-01	-3.87E-01	-3.78E-01	-2.54E-01	-4.16E-01
Percentile of deterministic value	28.20%	28.00%	33.00%	34.00%	46.40%	31.80%	57.40%	56.40%	42.80%	9.20%	27.00%	33.20%	49.60%

Table 9. Statistics for time to maximum flood elevation at 22.5 mile

Statistics	22.5 mile												
	Failure Cases							No-Failure Cases					
	ESFA	ESFB	ESFC	ETFF	EPFF	EPSF	FR12	ETFN	EPFN	EPSN	FR2B	FR3C	FR9
Deterministic value	1.20E+01	8.20E+00	7.60E+00	5.54E+01	5.12E+01	4.77E+01	5.31E+01	7.41E+01	6.60E+01	6.17E+01	5.81E+01	6.12E+01	5.82E+01
Mean	1.23E+01	8.31E+00	7.77E+00	5.55E+01	5.13E+01	4.78E+01	5.31E+01	7.41E+01	6.60E+01	6.17E+01	5.81E+01	6.13E+01	5.83E+01
Median	1.22E+01	8.30E+00	7.80E+00	5.54E+01	5.14E+01	4.78E+01	5.32E+01	7.41E+01	6.60E+01	6.17E+01	5.81E+01	6.12E+01	5.83E+01
Maximum	1.39E+01	9.55E+00	8.90E+00	5.64E+01	5.22E+01	4.88E+01	5.40E+01	7.57E+01	6.77E+01	6.31E+01	5.94E+01	6.27E+01	5.96E+01
Minimum	1.07E+01	7.30E+00	6.80E+00	5.46E+01	5.04E+01	4.68E+01	5.22E+01	7.24E+01	6.45E+01	6.03E+01	5.67E+01	5.98E+01	5.69E+01
Variance	3.68E-01	1.46E-01	1.54E-01	1.12E-01	1.20E-01	1.30E-01	1.23E-01	3.79E-01	3.52E-01	3.30E-01	3.13E-01	3.65E-01	3.01E-01
Skewness	6.31E-02	2.63E-01	5.63E-02	-6.83E-02	-3.69E-02	4.38E-02	4.26E-03	2.97E-02	1.51E-02	-4.05E-05	-4.30E-02	4.17E-02	-5.82E-03
Kurtosis	-4.53E-01	-8.01E-03	-1.02E-01	-2.84E-01	-3.64E-01	-3.79E-01	-4.36E-01	-6.58E-01	-8.30E-01	-8.89E-01	-6.24E-01	-8.68E-01	-6.69E-01
Percentile of deterministic value	31.40%	36.40%	27.20%	31.80%	28.80%	41.20%	46.60%	49.80%	48.40%	46.00%	46.40%	46.00%	46.20%

Table 10. Statistics for maximum flow at 7.88 mile

Statistics	7.88 mile												
	Failure Cases							No-Failure Cases					
	ESFA	ESFB	ESFC	ETFF	EPFF	EPSF	FR12	ETFN	EPFN	EPSN	FR2B	FR3C	FR9
Deterministic value	4.84E+05	1.90E+06	2.67E+06	3.41E+06	3.62E+06	3.65E+06	3.89E+06	5.36E+04	1.10E+05	1.56E+05	2.16E+05	1.60E+05	2.06E+05
Mean	4.83E+05	1.95E+06	2.69E+06	3.40E+06	3.61E+06	3.65E+06	3.85E+06	5.36E+04	1.10E+05	1.56E+05	2.16E+05	1.60E+05	2.06E+05
Median	4.82E+05	1.93E+06	2.66E+06	3.39E+06	3.59E+06	3.63E+06	3.84E+06	5.36E+04	1.10E+05	1.56E+05	2.16E+05	1.60E+05	2.06E+05
Maximum	5.61E+05	2.43E+06	3.35E+06	3.94E+06	4.15E+06	4.20E+06	4.44E+06	5.36E+04	1.10E+05	1.56E+05	2.16E+05	1.60E+05	2.06E+05
Minimum	4.26E+05	1.62E+06	2.23E+06	3.02E+06	3.21E+06	3.24E+06	3.43E+06	5.36E+04	1.10E+05	1.56E+05	2.16E+05	1.60E+05	2.06E+05
Variance	6.86E+08	2.06E+10	4.79E+10	3.29E+10	3.45E+10	3.46E+10	3.81E+10	2.19E+00	2.26E+02	9.76E+01	8.62E+01	3.72E+01	3.54E+01
Skewness	2.57E-01	6.50E-01	4.52E-01	2.83E-01	2.83E-01	2.90E-01	2.92E-01	-2.29E-01	-1.16E-01	2.91E-01	-2.17E-01	-1.66E+00	-1.67E-01
Kurtosis	-6.24E-01	4.40E-01	-2.59E-01	-4.93E-01	-4.19E-01	-4.02E-01	-3.53E-01	-3.82E-01	-9.69E-01	-2.25E-01	-4.84E-01	3.80E+00	-4.69E-01
Percentile of deterministic value	53.60%	40.60%	51.60%	55.00%	54.60%	54.20%	60.00%	42.20%	47.20%	58.00%	48.60%	49.60%	48.00%

Table 11. Statistics for maximum flow at 22.5 mile

Statistics	22.5 mile												
	Failure Cases							No-Failure Cases					
	ESFA	ESFB	ESFC	ETFF	EPFF	EPSF	FR12	ETFN	EPFN	EPSN	FR2B	FR3C	FR9
Deterministic value	1.33E+05	7.21E+05	1.32E+06	2.04E+06	2.26E+06	2.33E+06	2.48E+06	5.33E+04	1.08E+05	1.51E+05	2.11E+05	1.59E+05	2.02E+05
Mean	1.33E+05	7.23E+05	1.32E+06	2.02E+06	2.24E+06	2.31E+06	2.44E+06	5.33E+04	1.08E+05	1.51E+05	2.10E+05	1.59E+05	2.02E+05
Median	1.32E+05	7.20E+05	1.31E+06	2.01E+06	2.24E+06	2.31E+06	2.44E+06	5.33E+04	1.08E+05	1.51E+05	2.11E+05	1.59E+05	2.02E+05
Maximum	1.50E+05	8.26E+05	1.51E+06	2.30E+06	2.55E+06	2.63E+06	2.82E+06	5.34E+04	1.09E+05	1.53E+05	2.13E+05	1.59E+05	2.04E+05
Minimum	1.18E+05	6.46E+05	1.16E+06	1.81E+06	2.02E+06	2.09E+06	2.18E+06	5.32E+04	1.07E+05	1.49E+05	2.08E+05	1.58E+05	2.00E+05
Variance	5.27E+07	1.34E+09	4.89E+09	9.60E+09	1.27E+10	1.36E+10	1.71E+10	2.21E+03	1.80E+05	7.13E+05	1.24E+06	1.04E+05	5.97E+05
Skewness	1.49E-01	2.90E-01	2.41E-01	3.06E-01	2.96E-01	3.00E-01	3.20E-01	-2.23E-01	-1.81E-01	-1.90E-01	-1.89E-01	-2.97E-01	-2.33E-01
Kurtosis	-8.32E-01	-5.61E-01	-3.87E-01	-4.95E-01	-5.74E-01	-5.76E-01	-5.11E-01	-7.48E-01	-1.17E+00	-1.09E+00	-8.49E-01	-9.59E-01	-8.32E-01
Percentile of deterministic value	54.60%	51.00%	52.60%	59.40%	57.80%	58.20%	61.80%	48.60%	51.00%	50.20%	51.80%	49.20%	51.80%

sampling technique, called Latin Hypercube Sampling, instead of simple random sampling to save the computational time and resources necessary for a large number of model running.

This study determined the minimum number of model running that can cover the whole possible ranges of uncertain input parameters using two statistics (i.e., mean and variance) of the NWS FLDWAV model outputs. During the uncertainty model running, three FLDWAV model outputs (i.e., maximum flood elevation, time to maximum flood elevation, and maximum flood flow) at two locations (i.e., 7.88 and 22.5 mile) were recorded at each simulation of the NWS FLDWAV model, and their relative difference of two statistics at each scenario between 100, 200, 300, 400, and 500 simulations were calculated. The relative differences are displayed by the percentage in Figures 2 and 3.

Figures 2 and 3 show that the relative differences of two statistics are decreasing dramatically as the number of simulations is increasing. In particular, the relative differences of distributional mean and variance between 400 and 500 simulations are within the ranges of about 0.2 to +0.2% and 10.0 to +5.0%, respectively. It can be concluded that the relative differences of two statistics are decreasing as the number of simulations is increasing, although the decreasing rates of relative differences are reducing, as well. Therefore, no attempt was made to run more 500 simulations in this study, and this study concluded that 500 simulations were necessary and sufficient for this study purpose.

5. UNCERTAINTY IN THE MODEL OUTPUTS

500 sets of the flood routing results for 13 Alamo Dam breach/no breach scenarios were generated from the uncertainty runs of the NWS FLDWAV model using the Monte Carlo simulation. The key statistics such as mean, median, maximum, minimum, variance, skewness, and kurtosis were calculated from the 500 sets of the three flood routing results, i.e., maximum flood elevation, time to maximum flood elevation, and maximum flow, at the two damage centers, i.e., 7.88 and 22.5 mile, and they are summarized in Tables 6 to 11, respectively. In addition, this study employed the modified side-by-side boxplots to describe efficiently the identified uncertainty associated with the three flood routing results. The modified side-by-side boxplots used in this study display the seven summary statistics, i.e., 5th, 10th, 25th, 50th, 75th, 90th, and 95th percentile of the distributions. A line drawn across the box is the 50th, the bottom of the box is 25th, and the top is 75th percentile. The lines below and above the box are the 10th and 90th percentiles, and the dots beneath and over the lines are the 5th and 95th percentiles.

5.1 Uncertainty in the Maximum Flood Elevation

Figure 4 shows the variations of the estimated maximum flood elevation at the two damage centers in the downstream of Alamo Dam. It can be seen that the amount of variation is different with the defined the Alamo Dam breach/no breach scenarios. The amounts of variations for the sunny day failure cases (i.e., ESFA, ESFB, and ESFC) are greater than the no-failure cases (i.e., ETFN, EPFN, EPSN, FR2B, FR3C, and FR9), but less than the flood failure case (i.e., ETFF, EPFF, EPSF, and FR12). In addition, the amount of variation for each of the scenarios is reducing as the floods through Alamo Dam propagates along the river below the Alamo Dam.

The identified from Figure 4 could be numerically ascertained through the variance of the maximum flood elevations in Tables 6 and 7. These tables also provide information on the degrees of asymmetry and relative flatness of the distributions of predicted maximum flood elevations through skewness and kurtosis. The skewness ranges of the distributions of the maximum flood elevations are -0.06 to 0.38 at 7.88 mile and -0.02 to 0.18 at 22.5 mile and each value of skewness in Tables 6 and 7 is relatively small. Thus, this indicates that the degrees of asymmetry of the distributions of the maximum flood elevations are not much significant. In addition, all of the kurtosis values, except ESFB at 7.88 mile has 1.12, are negative in Tables 6 and 7 and are within -1.19 to -0.29 and -1.07 to -0.27, respectively. Therefore, this indicates that the distributions of the maximum flood elevations at two downstream locations are a little flat.

"Deterministic value" in Tables 6 and 7 means the maximum flood elevations at the two specified locations when uncertainty of the input parameters is ignored. "Percentile of deterministic value" represents the relative percentile of the deterministic value in the distribution of the maximum flood elevation obtained from the uncertainty model runs. For an example, the percentile of deterministic value for ESFA at 7.88 mile is 51.60%, so this indicates that there is a 48.40% chance that the predicted maximum flood elevation for ESFA exceeds the deterministic value (2.72E+02) while there is a 51.60% chance that the elevation is below the value. Therefore, the degrees of uncertainty in the deterministic maximum flood elevations can be directly interpreted from the percentile of deterministic values. The ranges of exceedance probabilities are 44.2 to 60.4% at 7.88 mile and 46.4 to 51.4% at 22.5 mile, respectively. Thus, this indicates that the deterministic maximum elevations have considerable amount of uncertainty. The variation ranges of the maximum flood elevations at the two locations were also calculated with the difference between the maximum and minimum values from Tables 6 and 7. The ranges are reached up to 39 ft in EPFF at 7.88 mile and 18 ft in ETFF, EPFF, FR12 at 22.5 mile.

5.2 Uncertainty in Time to the Maximum Flood Elevation

Figure 5 displays the variations of time to the maximum flood elevation at the two damage centers in the downstream of Alamo Dam. Although it is difficult to define directly the amount of variation for each scenarios from Figure 5, it can be seen that the amount of variation is increasing as the dam breach floods propagate along the valley below the Alamo Dam. Therefore, Figure 5 indicates that the amount of variation change as the defined scenarios and the flood routing distance from the dam.

Detailed distributional characteristics of time to the maximum flood elevation can be identified from the skewness and kurtosis in Tables 8 and 9. The skewness ranges of time to the maximum flood elevations are -0.33 to 0.47 at 7.88 mile and -0.07 to 0.26 at 22.5 mile. Thus, this indicates that the distributions of time to the maximum flood elevations are not much asymmetry. In addition, Tables 8 and 9 show that all kurtosis are negative except that ESFB and ESFC at 7.88 mile have the positive values, i.e., 0.27 and 0.005, respectively. Therefore, this means that most of distributions are a little flat, and the degree of flatness of the distributions are from -0.089 to - 0.097 at 7.88 mile and -0.008 to

-0.89 at 22.5 mile. Exceedance probabilities of time to the maximum flood elevation calculated with the deterministic values are 42.6 to 90.8% at 7.88 mile and 50.2 to 72.8% at 22.5 mile. In particular, EPSN has the maximum exceedance probability at 7.88 mile, while FR12 has the minimum. At 22.5 mile, the exceedance probability of ESFC is the largest, but ETFN is the smallest. The variation ranges are 0.2 to 1.9 hour at 7.88 mile and 1.8 to 3.3 hour at 22.5 mile.

5.3 Uncertainty in the Maximum Flood Flow

Figure 6 presents the variations of the maximum flood flow at the two consequence centers in the downstream of Alamo Dam. Figure 6 shows that the variation ranges of flood failure cases are greater than the sunny day failure cases, and no-failure cases are even less than the sunny day failure cases at the two downstream location. Figure 6 also shows that the variation ranges are decreasing as the floods through the Alamo Dam propagates along the river below the dam. Therefore, this indicates that the amount of variation of the maximum flood flow is different depending on the scenarios and the flood routing distance from the dam.

In Tables 10 and 11, the skewness ranges of the distributions of the maximum flood flows are -1.66 to 0.65 at 7.88 mile and -0.30 to 0.32 at 22.5 mile. In particular, it is interested that the distributions of the maximum flood flows for the sunny day and flood failure cases have the positive skewneess and no failure cases have the negative one. All kurtosis in Tables 10 and 11 are negative except that ESFB and FR3C at 7.88 mile have the positive values, i.e., 0.44 and 3.8, respectively. Therefore, it can be seen that most of distributions are a little flat, and the degree of flatness of the distributions are from -0.23 to -0.97 at 7.88 mile and -0.39 to -1.17 at 22.5 mile.

The exceedance probability ranges of the maximum flood flow are 40.0 to 59.4% at 7.88 mile, and ESFB has the maximum exceedance probability while FR12 has the minimum. The ranges at 22.5 mile are 38.2 to 51.4%, and the largest exceedance probability is ETFN and the smallest is FR12. The variation ranges of the maximum flood flow at the two downstream locations are about 0 to 1,120,000 cfs at 7.88 mile and 200 to 640,000 cfs at 22.5 mile. In addition, the variation ranges for the failure cases are greater than no failure cases. This means the estimated maximum flood flows through the valley of Alamo Dam may vary as the defined scenarios as well as the distance from the dam.

6. SUMMARY AND CONCLUSIONS

This study has performed uncertainty analysis for the dam breach flood routing analysis results using the NWS FLDWAV model. Two most uncertain input parameters, i.e., dam breach parameters and Manning's roughness coefficients, of the NWS FLDWAV model were selected to explain uncertainty in the predicted model outputs, and the Monte Carlo simulation technique based on Latin Hypercube Sampling technique was used to perform the uncertainty analysis. The outcomes and findings from this study as follows:

1. This study developed computer programs for conducting the uncertainty analysis with the NWS FLDWAV model, and identified through the application of the programs to the case study that three dam breach flood routing results, i.e., maximum flood elevation, time to maximum elevation, and maximum flow, are strongly affected by the two uncertain input parameters.

2. This study increased the efficiency and re-

duced the computational time of uncertainty analysis based on the Monte Carlo simulation by the Latin Hypercube Sampling technique.

3. The amounts of uncertainty included in the dam breach flood routing results are different by the locations from the dam and the model running scenarios, and the degrees of the uncertainty could be quantified numerically using the statistical analysis. In addition, the dam breach flood routing results with considering the uncertainty in the input parameters was compared to those without considering the uncertainty.

4. In order to perform the flood damage assessment or dam safety assessment mainly that heavily depend on the dam breach flood routing analysis results, uncertain parameters necessary for the dam breach flood routing analysis should be treated in a reasonable manner, and uncertainty in the dam breach flood routing analysis results must be systematically identified.

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