IMPACT OF DAM AND RESERVOIR PARAMETERS ON PEAK BREACH DISCHARGE PREDICTIONS FOR TWO MODELS

By

RONALD DWAIN TEJRAL

Bachelor of Science in Agricultural Engineering

University of Nebraska

Lincoln, Nebraska

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Thesis Approved:

Dr. Gregory J. Hanson

Thesis Adviser

Dr. Glenn O. Brown

Dr. Daniel E. Storm

Dr. A. Gordon Emslie

Dean of the Graduate College

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I must acknowledge the sacrifices made by my family, especially in the final months, which made it possible to complete this thesis. Many thanks and all my love to Mary Kate, Andrew, Anja, Gianna, and Eileen.

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CHAPTER I

INTRODUCTION

Dams are an important part of this nation's infrastructure providing flood control, water supply, irrigation, hydropower, navigation, and recreation. Despite their many beneficial uses, dams present a risk to property and life due to their potential to fail. They are also an aging infrastructure and without proper maintenance, repair, rehabilitation, and upgrading they pose additional risk of failure. There are approximately 80,000 dams on the National Inventory of Dams (NID) (USACE 2005). As an indication of the potential need, one estimate places the cost of rehabilitation of 75,000 non-federally owned dams at $36.2 billion dollars (ASDSO 2003). In order to evaluate the potential impact and risk of dam failure to life and property downstream it is necessary to determine the potential zone and timing of flooding. Additionally, evaluation provides a means for prioritizing rehabilitation of these structures by determining which ones pose the greatest risk of failure.

There are several methods used for analysis of dam failures and the resulting breach outflow hydrograph, varying from conservative rules of thumb to detailed process-based modeling. Once the breach outflow hydrograph is determined for a potential dam failure, methods of determining the flooding zone downstream of the structure likewise vary from conservative rough rules of thumb to detailed numerical routing methods. Methods used for analysis are often dictated by the level of detail and conservatism required. Wahl (1998) grouped the common methods for breach hydrograph evaluations into four categories; 1) process based methods, 2) parametric models, 3) empirical equations, and 4) comparative analysis. The last three methods rely on historical dam failure data whereas the first method is dependent on the physical processes of failure and input of breach failure parameters.

Parametric models, empirical equations, and comparative analysis developed from historical data have and continue to play an important role in characterizing the potential impact of a dam failure but have several shortcomings. 1) The number of well documented historical cases is small relative to the large number and wide variety of dams that exist and it is unclear whether the dams in historical failures are representative of the existing dams on the NID. 2) Historical data have high uncertainty (Wahl 2004, Wahl 1998). 3) The use of historical failure data inherently assumes a dam failure will occur, usually in a relatively short time. 4) Empirical equations neglect breach failure processes and impact of embankment materials.

Figure 1.1 has been prepared from reports of historical failures of 64 dams, showing the peak breach discharge versus dam height or height of water, dependent upon whether the dam was overtopped or failed by other means, respectively (Wahl 1998, Kalkanis et al. 1986, Kirkpatrick 1977). It is important to note the scatter in the data is as much as 3 orders of magnitude for a given dam height and appears to be greater for smaller dam heights. The distribution of dam heights for the historical failures in Figure 1.1 is shown in Figure 1.2. This distribution, although similar, is different from the distribution of dam heights for dams on the NID (Figure 1.3). This is also true as we compare reservoir storage for failed dams (Figure 1.4) versus dams on the NID (Figure 1.5). This corroborates the issues raised in items 1 and 2 in the previous paragraph. Additionally it raises an important question as to whether historical dam failures and the resulting peak discharge prediction methods are representative of what can be expected from dams on the NID.

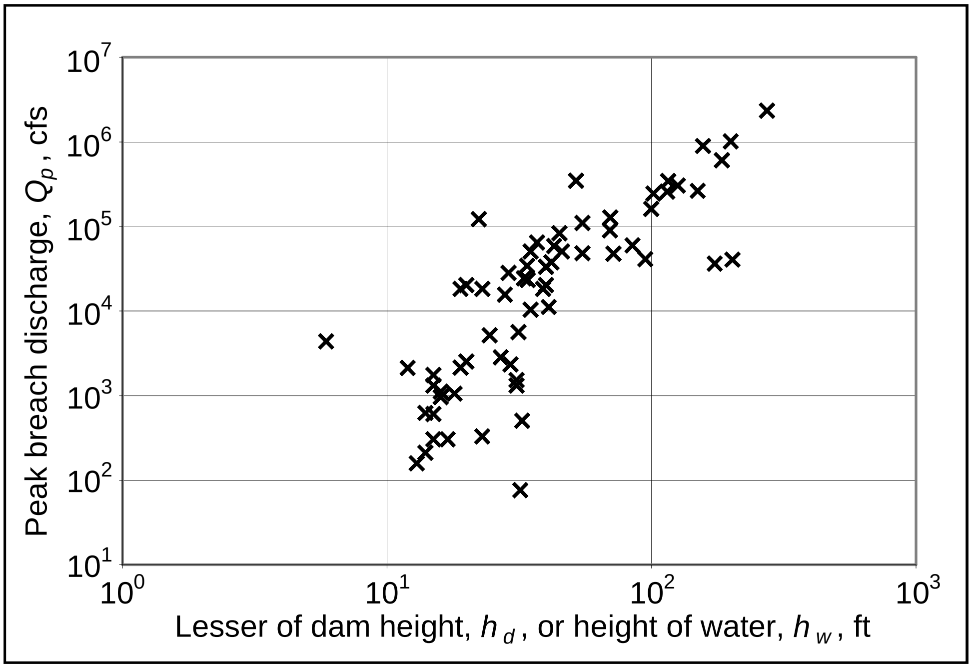

Figure 1.1 Peak breach discharge versus dam height, h_d, for overtopped dams and versus water surface elevation, h_w, relative to dam base for other failure modes (Wahl 1998, Kalkanis et al. 1986, Kirkpatrick 1977).

Ninety per cent of the NID are earthen dams (USACE 2005) and the two principle causes of earthen dam failure are overtopping and internal erosion (Singh 1996). However, Ralston (1987) reported on 27 SCS assisted dams known to have experienced overtopping and none had failed even though in some cases reservoir stages had reached three feet above the dam crest. Development of predictions based on historical failure data inherently implies a dam failure will occur and this is not necessarily the case.

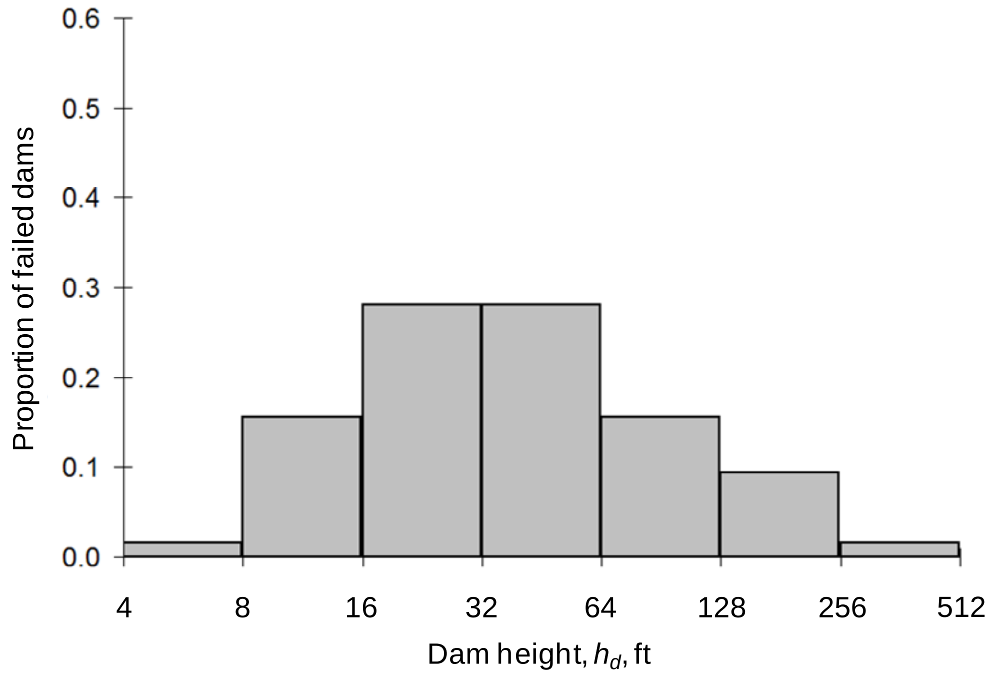

Figure 1.2 Histogram of heights of failed dams for which peak breach discharge was reported (Wahl1998, Kalkanis et al. 1986, Kirkpatrick 1977).

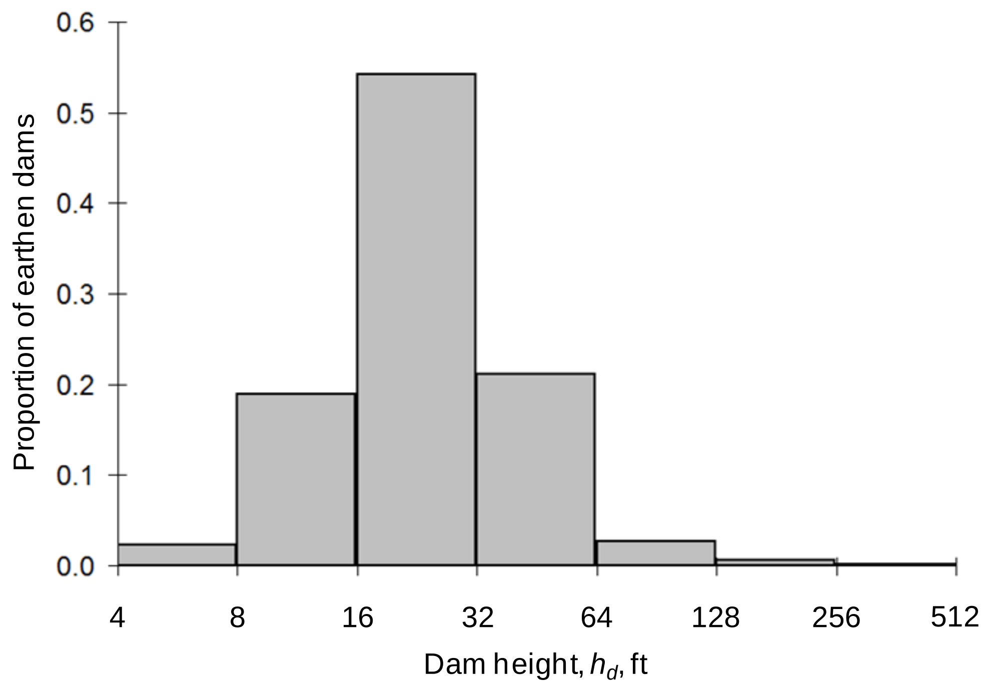

Figure 1.3 Histogram of heights of earthen dams in National Inventory of Dams (USACE 2005).

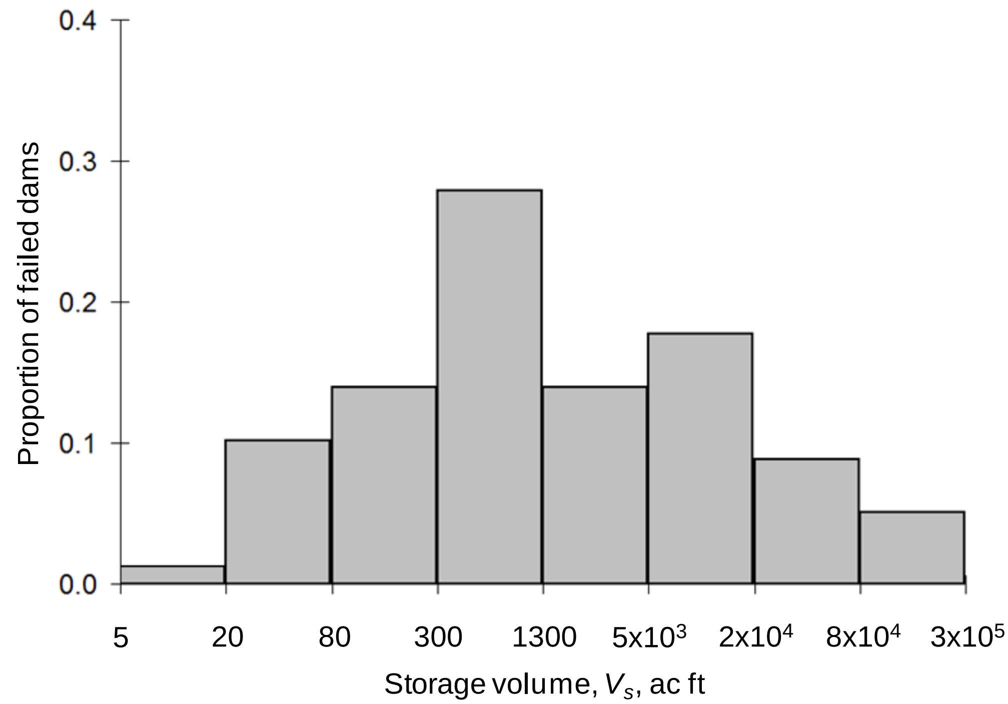

Figure 1.4 Histogram of reservoir storage volumes for failed dams (Wahl1998, Kalkanis et al. 1986, Kirkpatrick 1977).

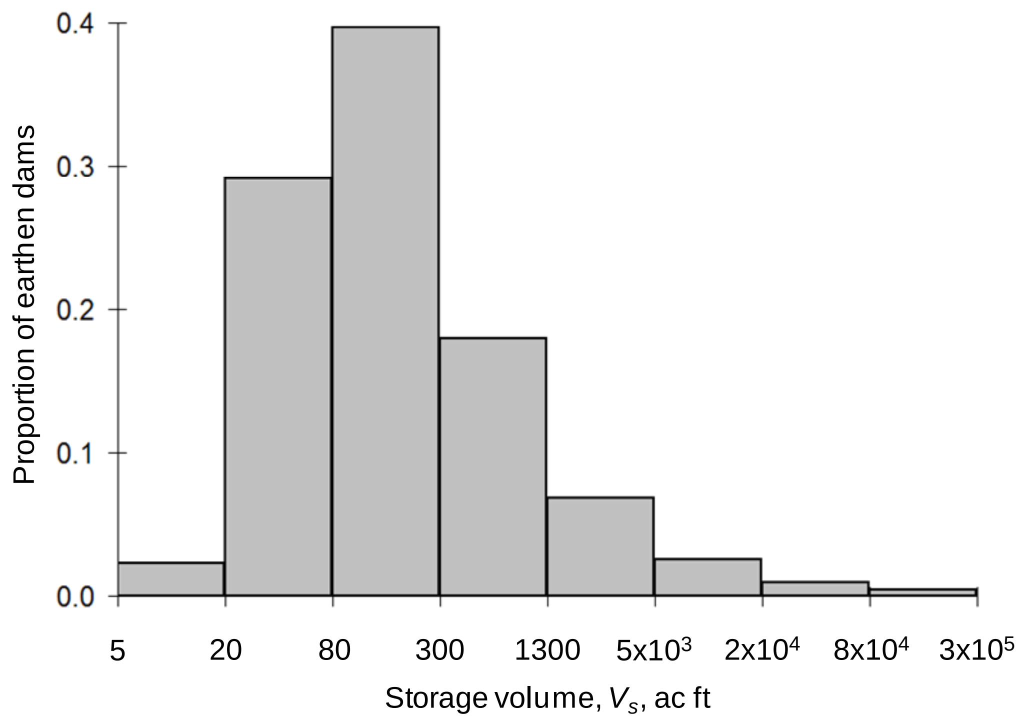

Figure 1.5 Histogram of reservoir storage volumes of earthen dams in National Inventory of Dams (USACE 2005).

Ralston (1987) reported observed patterns of erosion during overtopping for non-cohesive and cohesive soil embankments. The erosion pattern of non-cohesive soil embankments has been observed to be on a uniform but flattening gradient. Whereas, the pattern for cohesive soils has been observed to be development and migration of an overfall or headcut. Physical model overtopping tests conducted by the Agricultural Research Service (ARS) (Hanson et al. 2005) on soil embankments corroborate two of the observations by Ralston: 1) not all embankments fail during overtopping; and 2) the observed mode of erosion is development and advancement of an overfall (Figure 1.6). Hanson et al. (2005) provide a detailed description of these overtopping failure tests on 7.5 ft and 5 ft high cohesive embankments. Results from tests 1 and 2 of the overtopping tests provide a good example of the impact and the importance of incorporating material properties in computational model simulations. The embankment used in test 1 consisted of silty sand with 5 % clay and test 2 consisted of lean clay with 26 % clay. Figures 1.7 and 1.8 show discharge hydrographs results from tests 1 and 2, respectively. Test 1 failed

Figure 1.6 Downstream view of embankment overtopping experiment conducted by USDA Agricultural Research Service, Stillwater, Oklahoma in 1998. The observed steep overfall and migrating headcut are typical for embankments of cohesive material.

and resulted in a peak breach discharge in less than 1 hr of overtopping (Figure 1.7), whereas test 2 did not fail resulting in a peak discharge equal to the inflow during 20 hrs of overtopping (Figure 1.8).

The shortcomings of failure methods based on historical data, the observed processes of erosion and breach during overtopping, and the implications of material properties on breach failure point out the importance and usefulness for a process based model. Process based models are more difficult to apply and have shortcomings, but offer the capability of more detailed analysis of a potential dam failure including: failure or no failure, breach initiation time, variations of breach dimensions with time, and the breach outflow hydrograph. Process based computational modeling also allows for detailed interpretation of the impacts of embankment surface conditions, material properties, geometry, inflow, spillways, and reservoir storage.

Little work has been done to evaluate and compare process-based models to and in the context of other prediction methods. In this study two process based computational models are used to evaluate the implications of input parameters for the two ARS physical model test 1 and 2 and for a series of simulations based on synthetic data sets. The two process-based models are; 1) National Weather Service BREACH model (Fread 1991) used by the engineering community, and 2) SIMBA a research tool in development by USDA-ARS (Temple et al. 2006, Hanson et al. 2005, Temple et al. 2005) for eventual integration into WinDAM for use by the profession. The two are drastically different in the erosion equation used to predict erosion and the erosion process modeled. The NWSB is a sediment transport driven model whereas SIMBA is primarily a headcut migration model. The series of simulations will be contrasted with the NRCS envelope equation of the maximum breach discharge estimated from a historical set of breach discharges.

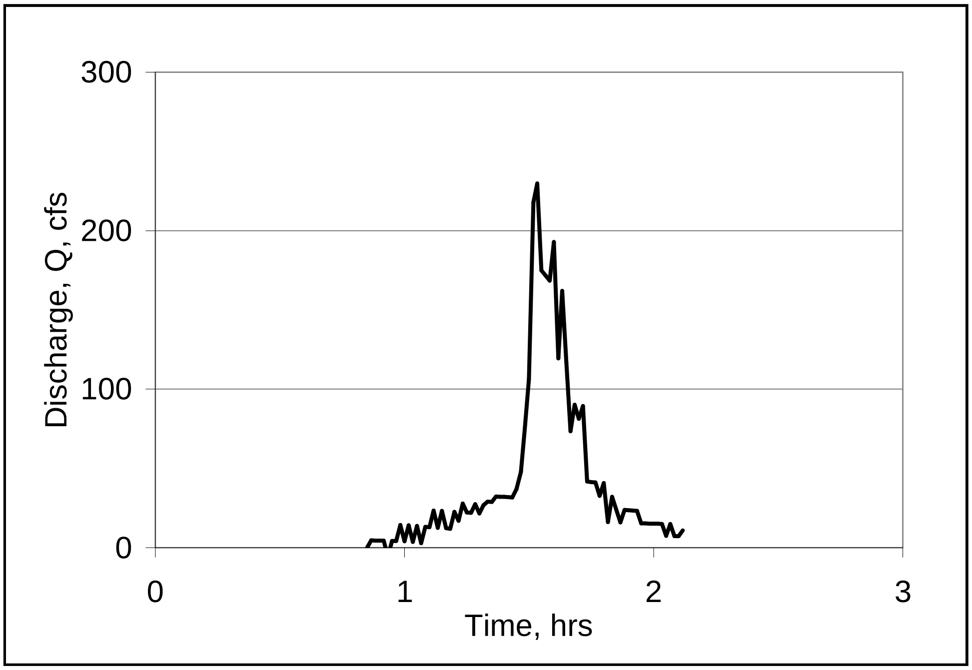

Figure 1.7 Measured discharge hydrograph of ARS overtopping test 1 (Hanson et al. 2005).

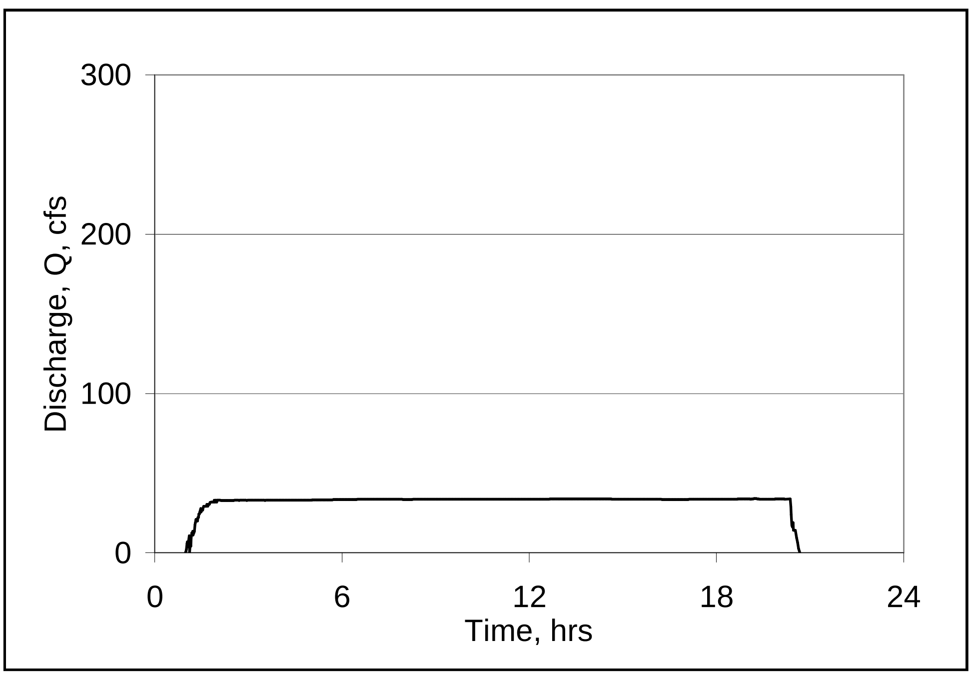

Figure 1.8 Measured discharge hydrograph of ARS overtopping test 2 (Hanson et al. 2005).

CHAPTER II

BACKGROUND

Following is a description of the two process based models used to evaluate input parameters for embankment overtopping breach analysis and the SCS empirical equation used as a base comparison to the synthetic data set results. The two process-based models used in this evaluation, National Weather Service BREACH (NWSB) model (Fread 1991) and SIMBA model (Temple et al. 2006, Hanson et al. 2005, Temple et al. 2005) are drastically different in the erosion equation and erosion process used in each. The two models provide a contrast to the two erosion processes observed by Ralston (1987). The NWSB is a sediment transport driven model simulating a uniform channel erosion process, while SIMBA is an excess stress erosion rate driven model simulating a discontinuity headcut erosion process.

National Weather Service BREACH

There have been numerous process-based breach models developed, but the best known is probably NWSB (Fread 1991), developed to evaluate both overtopping and internal erosion events. NWSB's principal erosion driver is the sediment transport relation developed by Meyer-Peter and Müller as modified by Smart for steep channels. Slopes for embankments typically range from 33-40% (Ralston 1987), which is beyond the recommended application range of 0.04 to 20% (Smart 1984). However, at the time

NWSB was developed the work by Smart was the state of the science. The relation as expressed by Fread (1991) in non-homogeneous form is:

$$Q_s = 3.64\left(\frac{D_{90}}{D_{30}}\right)^{0.2} P\frac{D^{2/3}}{n}S^{1.1}(DS-\Omega) \tag{2.1}$$

where Q_s = sediment transport rate, cfs,

D_{90} = particle size, mm, for which 90 percent is finer by weight,

D_{30} = particle size, mm, for which 30 percent is finer by weight,

P = wetted perimeter, ft, of channel cross section,

D = depth of flow, ft,

n = Manning roughness, dimensionless,

S = breach channel slope, dimensionless, and

Ω = threshold term, ft (defined in detail later).

Furthermore,

$\frac{D_{90}}{D_{30}}$ = uniformity, dimensionless.

Because it was the objective of this study to observe the effects of parameter variation, Equation 2.1 was examined to determine the material property most critical to the sediment transport process. The reader should note that there was no material property in Equation 2.1 that both directly and significantly affected the sediment transport rate.

The uniformity term, D_{90}/D_{30}, directly impacts rate; however taken to 0.2-power, it has little effect within a reasonable range of variation. Indeed a two-orders-of-magnitude increase in this ratio results in only a 2.5 increase in Q_s. A value of 1 would indicate a material with no material size variation from D_{90} to D_{30}. The default value of

(D_{90}/D_{30}) in NWSB is 10 which would represent a well graded gravel. A uniformly graded soil, representing a wide range of grain sizes from gravel to silts would have a value in the range of 50. Table 2.1 shows the potential range of the ratio of $(D_{90}/D_{30})^{0.2}$.

Table 2.1 Influence of D_{90}/D_{30} on the rate of sediment transport.

D_{90}/D_{30}	$(D_{90}/D_{30})^{0.2}$
1	1
10	1.58
100	2.51
1000	3.98

The threshold term, Ω, is determined by two different equations dependent on whether the material is cohesive. For non-cohesive soils,

$$\Omega = 0.0054\tau_c D_{50}, ft \qquad (2.2)$$

where τ_c = critical shear stress,lb ft^{-2}, and

D_{50} = particle size,mm,for which 50 percent is finer by weight.

For cohesive soils, Fread (1991) modified NWSB, but only adjusted the threshold term, Ω, not the rate aspects of detachment. This results in typically but not always a conservative estimate for cohesive embankments, relative to non-cohesive. For cohesive soils,

$$\Omega = \frac{b'}{62.4}(PI)^{c'}, ft \qquad (2.3)$$

where PI = plasticity index, dimensionless,

b' = empirical coefficient, $0.003 \leq b' \leq 0.019$, and

c' = empirical coefficient, $0.58 \leq c' \leq 0.84$.

Critical shear stress, τ_c, is a function of D_{50}, D, and S, and is sensitive to changes in D_{50} as well as D and S. However, in most instances $\Omega \ll DS$, and therefore the term $(DS - \Omega)$ is rather insensitive to changes in D_{50}. While Ω for cohesive materials is determined by PI and coefficients $b'$and c', the result is essentially the same, $\Omega \ll DS$. Thus, the distinctions between cohesive and non-cohesive are not important for meaningful discharges and stress encountered in a breach event.

Though changes in uniformity, D_{90}/D_{30}, and the threshold term, Ω, as determined by D_{50} or PI, exert direct influence on sediment transport rate, Q_s, the response to changes in these values is not strong. D_{50}, however, potentially plays a more significant role by determining n in Equation 2.1 and in turn impacts Q_s. By default, NWSB uses the Strickler relation (Fread 1991):

$$n = 0.013 D_{50}^{0.67} \tag{2.4}$$

Because n is positively correlated to D_{50}, but resides in the denominator of Equation 2.1, an increase in D_{50} results in a decrease in Q_s as one should expect. While a two-order-magnitude change in D_{90}/D_{30} or Ω yield only sub-order magnitude responses from Q_s, a two-order-magnitude shift in D_{50} elicits slightly more than a one-order-magnitude response from n and thus Q_s. Therefore it can be concluded that D_{50} is a key material parameter affecting Q_s. So it comes as no surprise that Fread (1991) identified “average” (median) particle size, D_{50}, among the most critical material properties.

The other properties singled out by Fread (1991) were internal friction angle, φ; cohesive strength, C. While not appearing in Equation 2.1, φ and C may affect the rate of breach development through stability and collapse computations. At each time step, NWSB considers whether the sidewalls of the breach are stable. If not, the unstable portion of the slope is assumed to have fallen into the breach flow. NWSB then checks the ability of horizontal sections of a dam to resist sliding due to the hydrostatic force on its upstream face. These two parameters may increase the rate of breach development by triggering instantaneous enlargement, which leads to increased discharge that in turn increases the sediment transport rate. Fread (1991) presented two examples where he found both φ and C could be either inversely or directly related to predicted peak breach discharge. There were also ranges of φ and/or C in these analyses for which peak discharge was insensitive to changes in the parameters.

To explain how the sediment transport and stability computations are used in the model, it is important to discuss the underlying process simulated within the overtopping breach portion of the model (Figure 2.1). It is assumed within the model that a predefined rectangular breach channel exists on the downstream face (Figure 2.1a). Once overtopping begins, it erodes downward parallel to the downstream face of the dam (Figure 2.1b). Therefore, lowering of the dam crest is delayed until the eroded channel reaches a depth slightly greater than the product of slope and crest width (Figure 2.1c and d). The quantity of material transported is modeled as taking place equally on the bottom and sides, i.e. the full wetted perimeter. However, the bottom width is assumed to be equal to a multiple of the critical depth of flow at the breach channel entrance. Additionally, breach width enlargement and a change of channel side slope may occur if it is determined that the sides are unstable (Figure 2.1e). Once a slope failure occurs, downward erosion proceeds only after the volume of the slide has been transported from the channel. Downward erosion is considered to cease once the upstream crest erodes to the base elevation of the dam and then erosion occurs strictly as breach widening (Figure 2.1f).

The routing of the reservoir is modeled based on conservation of mass. Bathymetry, spillway discharge, and reservoir inflow are determined from user input tables of elevation and area, head and discharge, and time and inflow rate, respectively. Additionally the spillway invert elevation is required. For overtopping and subsequent breach flow, the broad crested weir relationship is used to compute discharge. Using flow rate and bottom width, the Manning equation is solved for depth. The solution is iterative when the side slopes are not vertical. Computation time was a major consideration at the time of NWSB's development. Thus, a steady-state solution to the hydraulics was employed.

The original model was operated on mainframe computers, with data entry organized in 16 cards of no more than 8 variables defined in 10-character fields. Though NWSB has been adapted for personal computers, it runs in DOS and has no inherent user interface. Output is in the form of a text file which prints a table of inputs, a table detailing breach formation versus time, summaries of key outputs, and a hydrograph plot. Though not explored in this study, the NWSB provides for modeling of landslide dams, piping, zoned embankments, erosion of grass cover, and erosion through a one foot surface layer with material properties different from dam core.

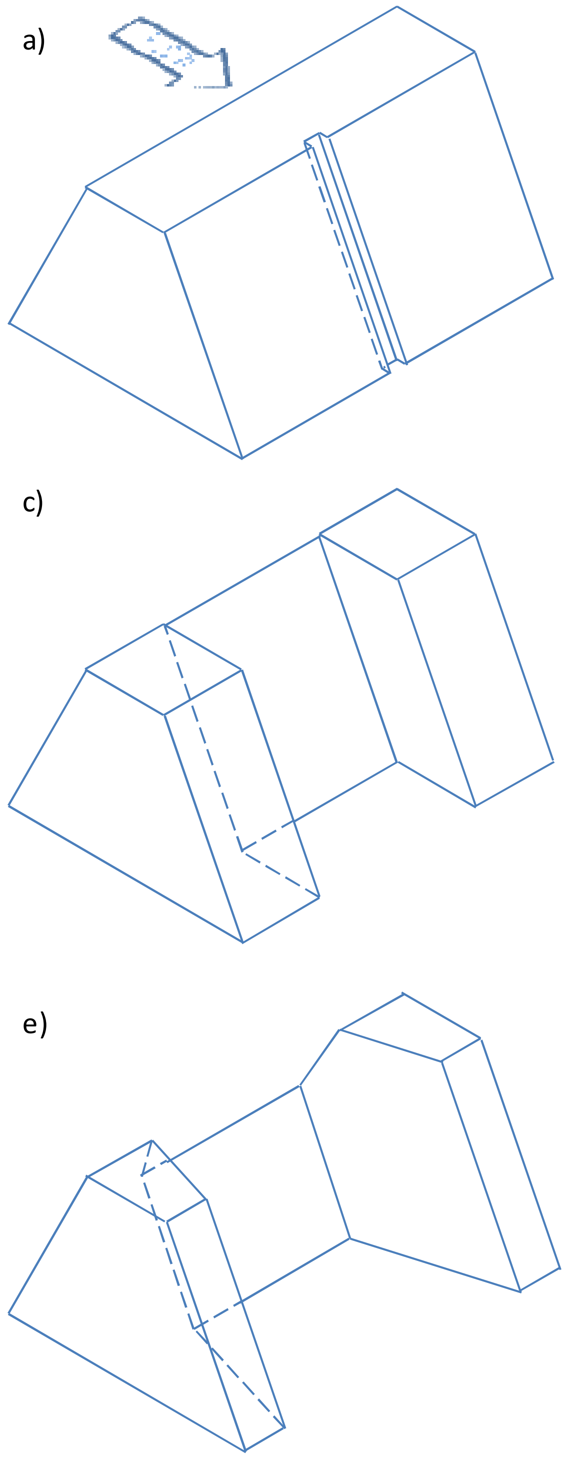

Figure 2.1 Sequence of breach development for an overtopped dam as conceptualized in National Weather Service BREACH. Discharge is from top left to bottom right of each figure. (a) From the first time step a small rectangular channel exists on the downstream face of the dam. (b) The channel erodes downward always parallel to downstream face, and (c) must erode through crest width before it enters reservoir. (d) Channel continues to deepen and widen. (e) Channel sides may collapse if they are determined to be unstable. (f) Breach opening may continue to widen after dam has been eroded to base.

SIMBA

The research underlying the SIMBA/WINDAM model development is driven by the need to evaluate existing NRCS dams. A majority of these dams are homogeneous earth fill. The large number of dams involved and the limited resources available for evaluation of each dam require that the final tool be as simple as possible while retaining the ability to simulate the dominant physical processes. Additionally, required inputs to the model, including the description of the embankment material, must be reasonably available. The model's name is taken from "Simplified Breach Analysis." Temple et al. (2006) provide additional discussion of the SIMBA/WINDAM development.

SIMBA is a computational model being developed for the purpose of analyzing earth embankment breach test data and extending the understanding of the underlying physical processes of breach of an overtopped earth embankment. It is a research tool that is modified routinely to test the sensitivity of the output to various sub-models and assumptions (hence the status of "being developed"). SIMBA is a part of a larger Windows Dam Analysis Modules (WINDAM) project that is envisioned as a field tool for dam design and evaluation that includes breach simulation. Work is presently underway to incorporate components of SIMBA into the WINDAM software and component validation studies are ongoing. It also anticipated that future generations of SIMBA will evaluate zoned embankments and internal erosion.

In its present form, SIMBA is limited to the evaluation of overtopping of homogeneous earth embankments with negligible protection on the downstream face. The model simulates four stages of the failure process observed for these embankments (Hanson et al. 2005). 1) Surface erosion leading to development of a headcut on the downstream face of the embankment. 2) Headcut advance through the crest to initiate the breach. 3) Breach formation as the headcut advances into the reservoir. 4) Breach expansion during reservoir drawdown.

The model as described herein represents only that part of the overall research tool that presently appears to best represent the processes associated with these stages in the simplest possible form. SIMBA and example application are discussed by Temple et al. (2005) and Hanson et al. (2005). With the exception of the headcut advance model being used, these earlier discussions are consistent with the present model. The 2005 discussions focused on an energy-based headcut advance model whereas the model used here employs a stress-based headcut advance prediction (Hanson et al. 2001). SIMBA as described in this paper utilizes the stress-based detachment rate model for all four stages of the erosion computations. The keys to this model, are the algorithms defining the hydraulic stress applied during each stage and the material parameters defining the resistance to erosion. The governing excess shear detachment rate relation is:

$$\dot{\varepsilon} = k_d(\tau - \tau_c) \tag{2.5}$$

where $\dot{\varepsilon}$ = the erosion rate, $ft^3\ ft^{-2}\ hr^{-1}$,

k_d = detachment rate coefficient, $ft^3\ lb^{-1}\ hr^{-1}$,

τ = applied boundary stress, lb ft^{-2}, and

τ_c = critical stress required to initiate detachment for the material, lb ft^{-2}.

In contrast to NWSB, SIMBA utilizes a more basic version of the excess stress equation which requires the user to define k_d and τ_c for the soil of interest. The primary driver for breach erosion is the detachment coefficient, k_d with the critical stress, τ_c, playing a secondary role. The k_d value can be measured (Hanson and Cook, 2004, Wan and Fell 2004, Briaud et al. 2001), and has been observed to vary over several orders of magnitude (Hanson et al. 2005, Hanson and Simon 2001, Wan and Fell 2004).

Based on Equation 2.5, erosion occurs if the hydraulic stress is capable of detaching the particle from the soil matrix. Using an erodibility rate dependent model allows for seamless movement from cohesive soils of significant clay content (usually more erosion resistant) to non-cohesive soils of lower clay content, as long as the material is detachment limited. The removal of soil material occurs either due to shear stress of flow over the surface, or to shear stress from plunging action of the flow once a headcut has developed.

Erosion rates and the progression of the breach through the four stages are dependent on the discharge and the stage of the erosion process (Figure 2.2). Initial condition is an intact embankment of unprotected earth (Figure 2.2a). Erosion is considered to be in stage 1 of the breach process when the headcut is not formed to a height greater than the critical depth of flow and is located within or downstream of the crest (Figure 2.2b). Initial location of headcut formation is conservatively taken as the downstream edge of the crest. Erosive attack for this stage is computed from the approximation of a normal depth of flow on the slope with a Manning's *n* value for soil of 0.02. Hydraulic shear can then be calculated and the rate of material removal computed through the use of Equation 2.1. Under these conditions, the developing headcut deepens and widens, but does not advance. Breach widening rate of the area is taken as 1.4 times the rate of deepening (Chow 1959).

When the headcut height is greater than the critical depth of flow, the flow is considered plunging and the headcut will advance upstream as well as deepen. Stage 2 of the erosion process is the advance of the headcut through the crest (Figure 2.2c). The present test version of SIMBA uses the stress-based headcut advance model described by Hanson et al. (2001) modified to limit the advance rate computed for unstable headcut heights. Stresses at the base and on the face of the headcut are computed using the relations given by Robinson (1992) for a non-aerated condition. In the case that the headcut reaches an unstable height based on soil strength, the advance is limited by erosion based on detachment rate for normal depth flow on a slope of 0.5 horizontal to 1 vertical using the same assumptions as used when computing this stress elsewhere in SIMBA (Figure 2.2d). This is recognized as a major simplification of a complex process and is used only for the limiting condition indicated. The widening of the eroded area as a result of plunging action is taken to be equal to the rate of headcut advance.

As the headcut enters the reservoir (stage 3) the elevation of the hydraulic control is dependent on the position of the headcut (Figure 2.2e). The relations used to compute the headcut advance due to plunging action are the same as those described in stage 2. The rate at which the hydraulic control would be lowered by the hydraulic stress associated with critical flow over the brink is also computed. When this rate exceeds that computed for plunging action (note when headcut height is less than critical depth, the rate of headcut advance due to plunging action is zero). Then this downward erosion of the hydraulic control is considered to govern. When stress governs the erosion process, the widening of the breach is again computed as proportional to the stress-generated detachment rate.

Once the embankment is locally removed to the toe of the embankment (base of the headcut is bounded by this elevation in preceding stages), then only widening can occur (stage 4) (Figure 2.2f). The widening is assumed to be proportional to the applied stress for critical flow conditions (similar to the stress-controlled portion of stage 3). Stress on the banks is considered to be approximately 0.7 times the maximum stress that would be computed for the bed section in the rectangular breach section. Thus, for small values of critical stress, the widening rate would be approximately 1.4 times the detachment rate associated with stress on the bed.

Soil parameter inputs used to describe the embankment material in SIMBA are the total unit weight, undrained shear strength, detachment rate coefficient, and critical shear stress associated with initiation of detachment. SIMBA was programmed using Visual Basic and features a multi-page graphical user interface. It allows for pasting as well as direct entry. Additionally the input file created is editable text. While its output resides in a potentially lengthy text file, it features many graphical tools for examining results.

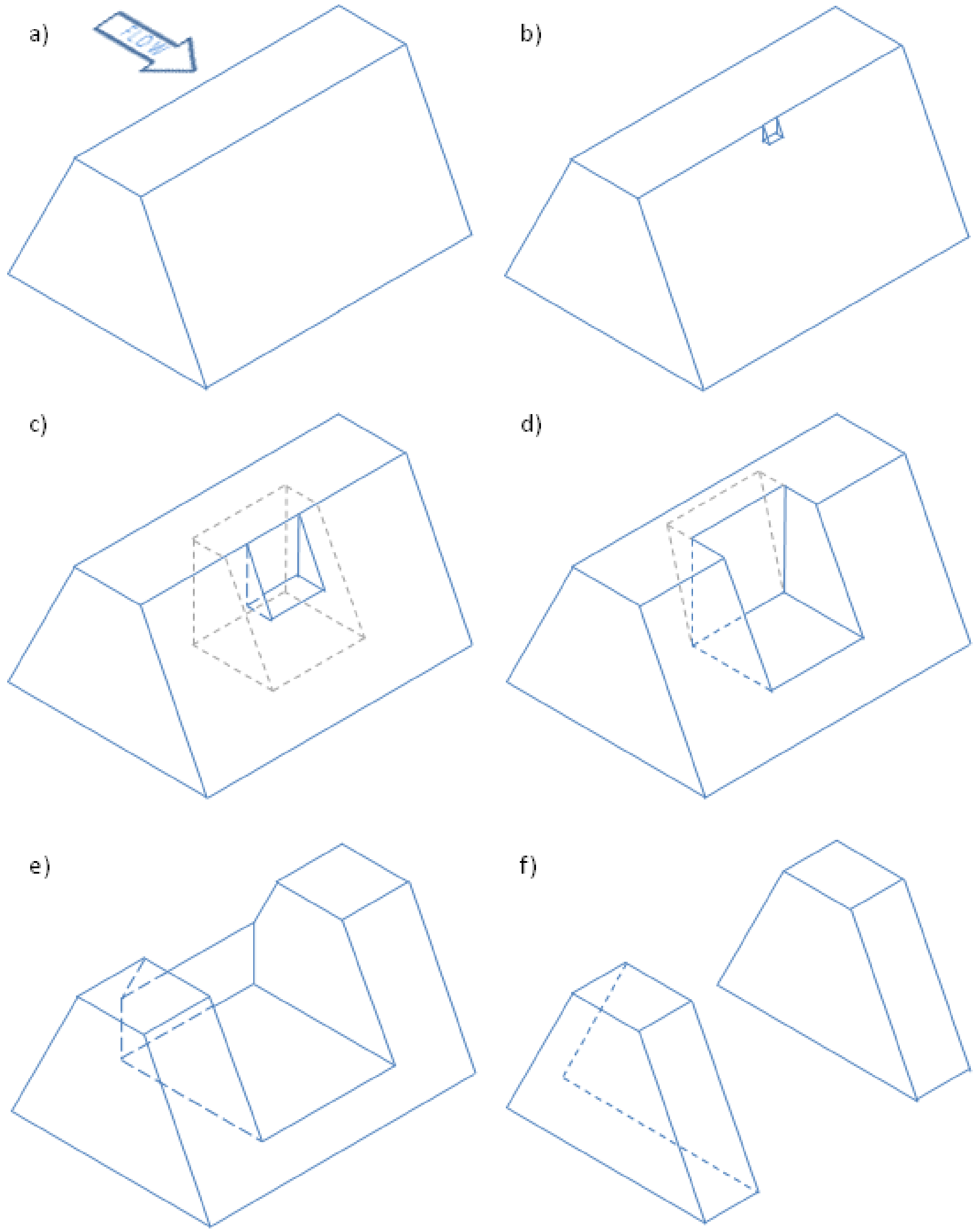

Figure 2.2 Sequence of breach development for an overtopped dam as conceptualized in SIMBA. Discharge is from top left to bottom right of each figure. (a) The simulation initiates with embankment intact. (b) A headcut forms at the edge of the downstream crest, (c) where it deepens and widens. Advance in to crest (gray, dashed lines) occurs when headcut height achieve critical depth. (d) Headcut continues to deepen and widen. Vertical face of headcut may become unstable and collapse (gray, dashed lines). (e) Breach formation occurs as headcut enters reservoir. (f) Breach opening may continue to widen after dam has been eroded to base.

SCS Equation

The authors of SCS Technical Release No. 66 (SCS 1979) noted simply that the expected maximum discharge of a breached dam depends upon failure rate and dimensions of the breach opening. Because the purpose of the release was to make available a “simplified” method for routing the hydrograph of a breached embankment, they proposed the maximum discharge be empirically based. The equation hereafter referred to as the “SCS equation”:

$$Q_p = 65H^{1.85} \tag{2.6}$$

where Q_p = peak breach discharge, cfs, and

H = elevation of reservoir water surface or crest of dam relative to dam base at failure, ft.

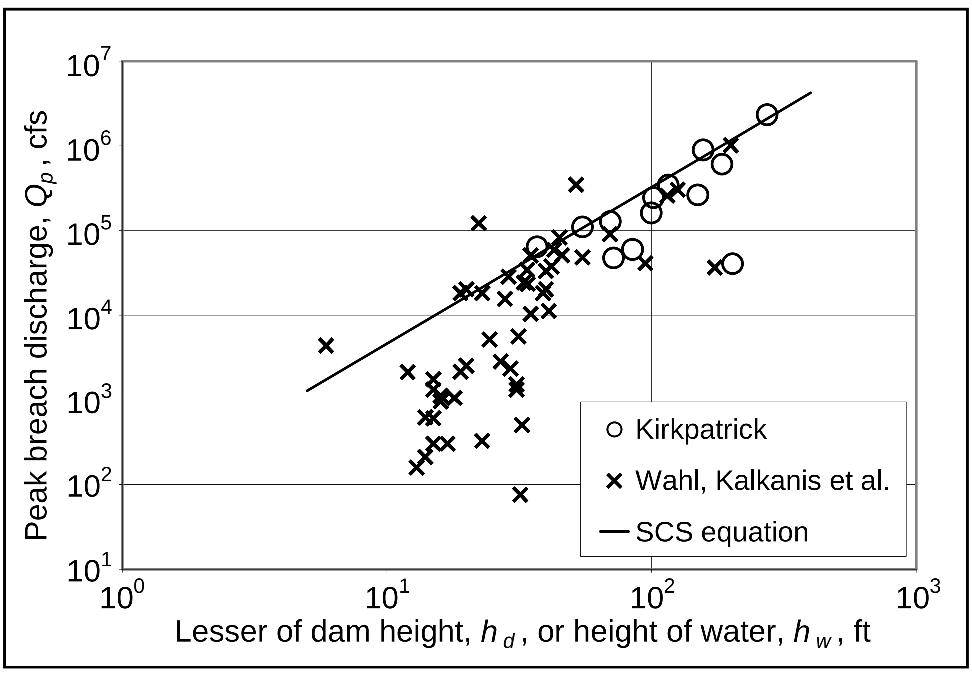

Figure 2.3 The data used by the Soil Conservation Service (Kirkpatrick 1977) to create the upper envelope equation of peak breach discharge (SCS 1979), is plotted with a larger data set comprised of compilations by Wahl (1998) and Kalkanis et al. (1986). For dams that failed by overtopping, the peak breach discharge, Q_p, is plotted against height of dam, h_d. For dams that failed by other modes, Q_p is plotted against the height of water in the reservoir, h_w, relative to the base of dam.

as depicted in Figure 2.3 is an approximate upper envelope (SCS 1979) of 13 failure cases published by Kirkpatrick (1977). Dam types included variations on earthfill, rockfill, and one concrete gravity structure, while failure modes were internal erosion, overtopping (Wahl 1998), and failure to design for uplift (Singh 1996). The method was later refined to allow lower estimates for embankments less than 103 ft high. Considerations were also made for reservoir storage, embankment cross-sectional area, and valley geometry that may reduce peak discharge, but the SCS equation remained the basis (SCS 1985). The Natural Resources Conservation Service continues to support its use in the most current technical release (NRCS 2005).

CHAPTER III

METHODOLOGY

NWSB and SIMBA have data input requirements and boundary condition assumptions in common, but also have data and input requirements that are unique to each specific model. The following describes how specific input requirements and boundary conditions were handled in developing data sets and conducting model simulations for ARS test data sets 1 and 2 and the synthetic data sets. The ARS test data sets 1 and 2 were from tests on embankments for which material properties differed, but geometry and hydraulic stresses were similar. Development of the data sets for tests 1 and 2 for NWSB and SIMBA did not result in any unique challenges with the exception of consistent handling of the unit discharge for NWSB, as explained at the end of this chapter. However, the synthetic sets were challenging. They had to be fashioned in a manner that was simple and to some extent consistent with the data for historical dam failures with the intent to evaluate model performance and parameter impact on breach peak discharge. The synthetic sets therefore featured a range of embankment heights, storage volumes relative to height, reservoir shapes, and parameters affecting erosion rate as applicable to each of the models.

ARS Test Data Sets 1 and 2

The ARS test data sets 1 and 2 were physical model overtopping tests conducted by the USDA ARS, Stillwater, Oklahoma (Hanson et al. 2005). Table 3.1 provides a summary of key data inputs for tests 1 and 2 and Appendices B and C provide additional details. Physical model tests were conducted by the USDA ARS, Stillwater, Oklahoma (Hanson et al. 2005) and were nearly identical in geometry, reservoir storage, and rate of inflow but differed in material properties. The NWSB and SIMBA models were used to estimate peak breach discharges for the two laboratory experiments using inputs determined from laboratory measurements. The exception was material properties for

Table 3.1 Model inputs from ARS overtopping tests 1 and 2.

Property	units	Test	
		1	2
Embankment height, h_d	ft	5.8	5.8
Crest length	ft	6	6
Crest width	ft	15	16
U.S. slope	H:V	3	3
D.S. slope	H:V	3	3
Plasticity index, *PI*		non-plastic	17
Bulk density, ρ_b	lb ft^{-3}	107	103
Porosity, f		0.30	0.28
Unconfined Compressive Strength, q_u	lb ft^{-2}	420	1400
Erodibility, k_d	ft^3 lb^{-1} h^{-1}	5.8	0.022
Critical stress, τ_c	lb ft^{-2}	<0.01	0.3
D_{30}	mm	0.075	0.0043
D_{50}	mm	0.14	0.014
D_{90}	mm	0.38	0.46
Reservoir shape, *m*		1.3	1.3
Nominal overtopping depth	ft	1.0	1.4
Overtopping duration	hr	0.3	18.8

NWSB; soil friction angle ϕ, cohesion C and the critical stress τ_c. The parameters ϕ and C were estimated based on a description of materials (Sowers and Sowers 1970). Critical shear stress, τ_c, is not a direct input for NWSB but rather is estimated by other material inputs. Therefore its values were determined by NWSB dependent on the choice of non-cohesive (test 1) or cohesive (test 2).

For test 1, a headcut advanced through the 15-ft crest in 37 minutes of overtopping and produced a peak discharge of 230 cfs. For test 2, a headcut advanced 9 ft into the crest in 20 hours of overtopping but did not breach. Discharge hydrographs for the tests 1 and 2 are reported in Chapter I and plotted with model output in Chapter IV.

Synthetic data sets

In this study, the two models NWSB and SIMBA were used to evaluate the impact of the variation of specific parameters on the peak breach discharge. It was not within the scope of this study to evaluate all parameters due to the number of possible parameters and variations. Thus, the most important parameters were selected from those identified in the literature: dam height, reservoir storage volume and shape, and key material parameters affecting erosion. The evaluations were conducted using a series of consistently varied synthetic data sets.

In order to use the two models to conduct the evaluations, it was necessary to understand the input requirements and limitations of each model so consistently similar data sets could be developed. The following discussion describes how the input data sets were constructed in a consistent manner including what parameters were held constant, what parameters were varied, what parameters were different between models, and challenges to formulate consistency in simulation runs.

Constant Parameters

For the purposes of the overtopping simulations conducted in this study, certain aspects of the simulated embankments were held constant including: the embankment geometry (embankment slopes and crest width), specific material parameters, overtopping depth and unit discharge, and time steps.

Geometry. The embankment geometry used in the simulations included upstream and downstream slopes of 3H:1V (horizontal to vertical), and a crest width of 0.1 ft (Figure 3.1). An upstream and downstream slope of 3H:1V was chosen because this is a common embankment slope (Ralston 1987). The crest width of 0.1 was chosen to minimize the breach initiation phase for each model. Both of these geometry parameters, slope and crest width, should be included in future investigations of parametric impacts.

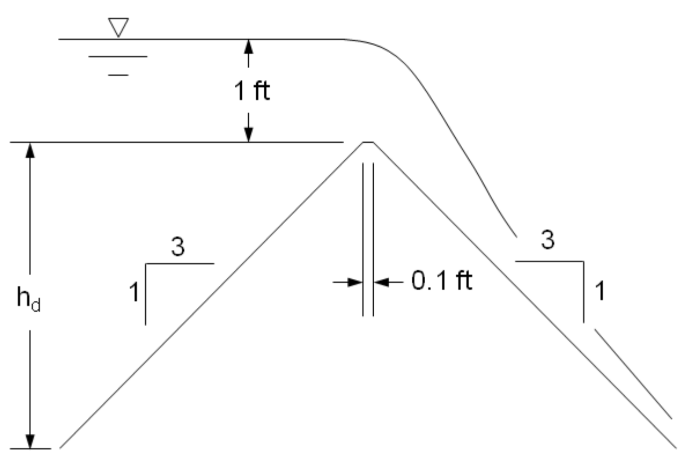

Figure 3.1 Generalized cross section and initial hydraulic conditions of synthetic dams.

Material properties. The material properties for NWSB and for SIMBA were held constant with the exception of D_{50} for NWSB and k_d for SIMBA, which were considered to be the key erosion parameters. These two parameters were varied as described later in the V*aried Parameters* section. Both models have at least one input defining structural strength of material. In SIMBA, undrained shear strength, C_u, is the only parameter used to specify strength. NWSB uses cohesive strength, *C*, and internal friction angle, φ. There is not enough information to relate strength as defined in one model to the other. For NWSB, the combination of parameters was cohesive strength, C = 250 lb ft^{-2}, porosity ratio, f = 0.3, dry bulk density, ρ_b = 110 lb ft^{-3}, internal friction angle, φ = 32°, uniformity, D_{90}/D_{30} = 10, and median particle diameter, D_{50} = 5mm. For SIMBA, the material parameters were C_u = 1000 lb ft-2, and as in NWSB, ρ_b = 110 lb ft^{-3}.

Overtopping and unit discharge. One of the challenges considered important was a consistent approach to drawdown during the breach initiation phases during overtopping. This was considered important so unit discharge and thus the hydraulic energy associated with breach initiation would be effectively constant for all simulations. In order to accomplish this, dam crest lengths were adjusted such that, assuming the crest was intact, the time required to draw down the reservoir from the elevation of 1 ft above the dam crest to the elevation of the dam crest was approximately the same for all simulations. The smallest dam (h_d = 5 ft, Storage *LP*, *m* = 3, see *varied parameters* below) was assigned an arbitrary crest length of 0.2 ft. The unit discharge versus time for each dam was matched to the smallest by adjusting crest length to achieve the lowest sum of squares difference in water surface elevations relative to crest elevation. The results were checked against the analytical solution for complete drawdown of the storage above the crest, and were found to compare favorably with a maximum difference of 6%. Crest lengths used in the model simulations are shown in Table 3.2. Development of the analytical solution, an example of the numerical solution, and a complete table of crest lengths as computed by both methods are found in Appendix D.

Table 3.2 Equivalent crest lengths for simulated data sets.

		Crest Length (ft)				
		baseline and erodibility variations	Varied parameter			
			m		Vs	
h_d-*S* curve		*UP*	*UP*	*UP*	*R*	*LP*
m		3	1	2	3	3
h_d (ft)	5	317	83	187	8.0	0.20
	10	539	160	340	13.3	0.33
	20	969	300	630	23	0.56
	50	2,195	710	1,440	52	1.21
	100	4,141	1,360	2,700	95	2.2
	200	7,861	2,600	5,200	177	4.0
	400	14,971	5,000	10,000	330	7.3

Time steps. While no formal study of sensitivity to time step was carried out, it is acknowledged that time step selection is important. For NWSB it is stated that the basic time step should be about 0.02 hours for most applications (Fread 1991). Most of the simulations were conducted at a time step of 0.02 hrs; the exceptions were for simulations in which storage was less than the *UP* curve, the time step was 0.01 hrs. For most of the SIMBA runs, a time step of 0.02 hrs was also employed. Smaller time steps were used in instances where changes were occurring rapidly.

Parameters held constant for the NWSB and SIMBA are summarized in Table 3.3. To the degree practicable, the simulation sets were developed and applied similarly to NWSB and SIMBA.

Table 3.3 Parameters held constant for synthetic data sets.

Property	Unit	Model	
		NWSB	SIMBA
crest width	ft	0.1	
U.S. slope	H:V	3	
D.S. slope	H:V	3	
Dry bulk density, ρ_b	lb ft^{-3}	110	
Porosity, f		0.30	-
Friction angle, φ	Degrees	32	-
Coshesive strength, C	lb ft^{-2}	250	-
Undrained shear strength, C_u	lb ft^{-2}	-	1000
Critical stress, τ_c	lb ft^{-2}	*	0.2
Uniformity, D_{90}/D_{30}		10	-
Initial head on crest	ft	1.0	

* function of D_{50}, D.S. dam face slope, and depth
- not an input for the model

Varied Parameters

Dam height. It was desired to model a range of embankment heights that cover the range of case history failures. Seven embankment heights, h_d, were used in the simulations: 5, 10, 20, 50, 100, 200, and 400 ft.

Storage volume (relative to height). For the purpose of examining the impact of changes in reservoir volume, three relationships of storage volumes to height were developed to cover the range of failed dams. These relations were determined from a power series regression of failed dams for which both height and storage data were reported (Wahl 1998, Kalkanis et al. 1986). Storage volume for each dam height was then determined based on the curves representing the regression relation, *R*, and the 95% prediction intervals, *UP* (upper prediction) and *LP* (lower prediction), respectively.

Storage volume to height relations are of the form:

$$V_S = \beta h_d^{\alpha} \tag{3.1}$$

where V_S = Storage volume at dam crest, ac ft

h_d = height of dam, ft,

β = coefficient, dimensionless, and

α = coefficient, dimensionless.

The curves are plotted with the data from which they were developed in Figure 3.2 and the coefficients are summarized in Table 3.4. It is interesting to note that the volume of storage varies three orders of magnitude for failed dams between the upper and the lower 95% prediction intervals.

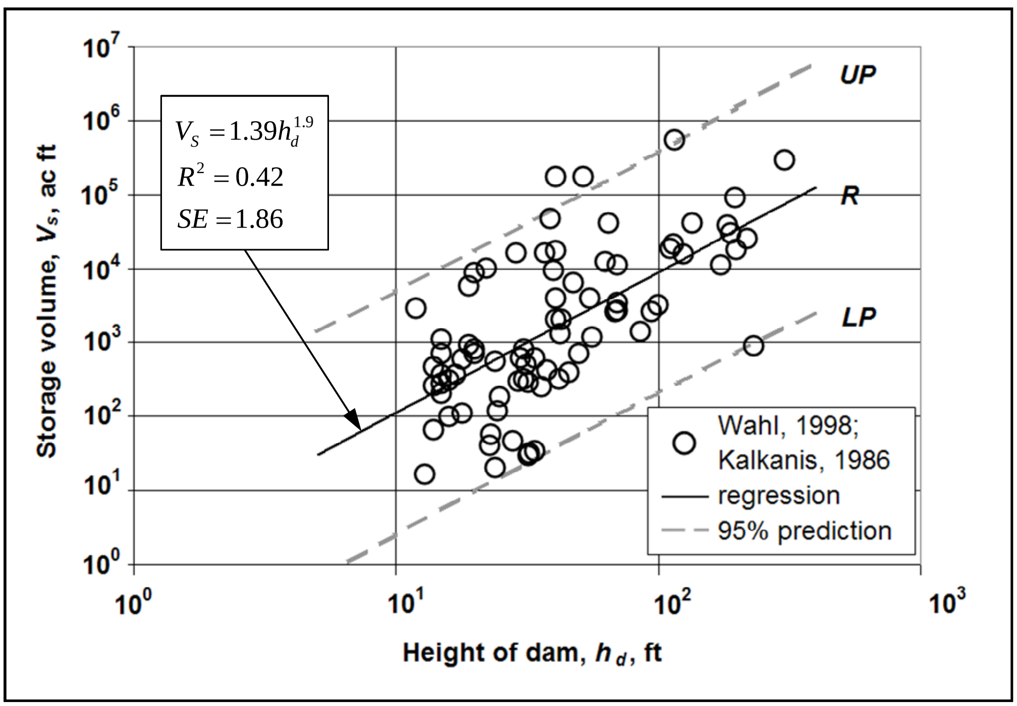

Figure 3.2 Dam height, h_d, versus storage volume, V_s, of failed dams (Wahl 1998, Kalkanis et al. 1986) with power series regression, *R*, and 95% confidence prediction interval defined by upper prediction, *UP*, and lower prediction, *LP*.

Table 3.4 Storage curve coefficients α and β for volume to height relationships of power series regression, *R;* and upper and lower bounds of 95% prediction envelope, *UP* and *LP*, respectively.

	coefficients	
Storage	β	α
UP	53	1.9
R	1.39	1.9
LP	0.037	1.9

Reservoir shape. The impact of reservoir storage shape was evaluated. Stage-storage relationships were developed based on a hypsometric function of the form (Walder and O'Connor, 1997):

$$\frac{V}{V_S} = \left[\frac{h}{h_d}\right]^m \tag{3.2}$$

where V = volume of water in reservoir, ac ft,

h = reservoir level, relative to base of dam, ft, and

m = exponent related to reservoir shape.

Therefore the height-to-storage relationship, stage-storage, was defined as:

$$V = \beta h_d^{\alpha - m} h^m \tag{3.3}$$

Walder and O'Connor (1997) referred to the exponent *m* as a shape factor with a range of interest in their study of 1 to 3; *m* = 1 represents a reservoir with vertical walls and flat floor, while *m* = 3 corresponds to a reservoir with walls and floor at a constant slope. Values of *m* = 1, 2, and 3 were used in the simulations. Figure 3.3 depicts idealized reservoir shapes for the shape factors, *m*, used in the study, while Figure 3.4 shows the generalized relationship of storage volume, *V*, to height, *h*.

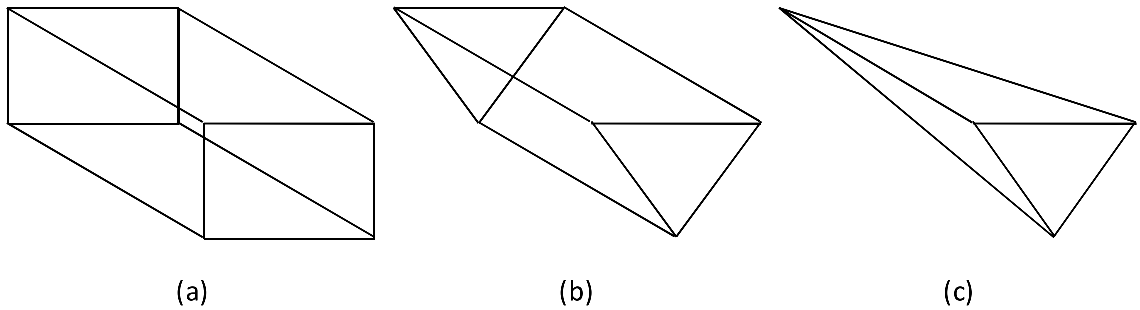

Figure 3.3 Idealized reservoir shapes for reservoir shape factor, *m*. (a) A reservoir of shape factor *m* = 1 has vertical walls and a flat bottom. (b) A reservoir of shape factor *m* = 2 has a horizontal bottom with walls of constant slope. (c) A reservoir of shape factor *m* = 3 has sides and bottom with constant slope.

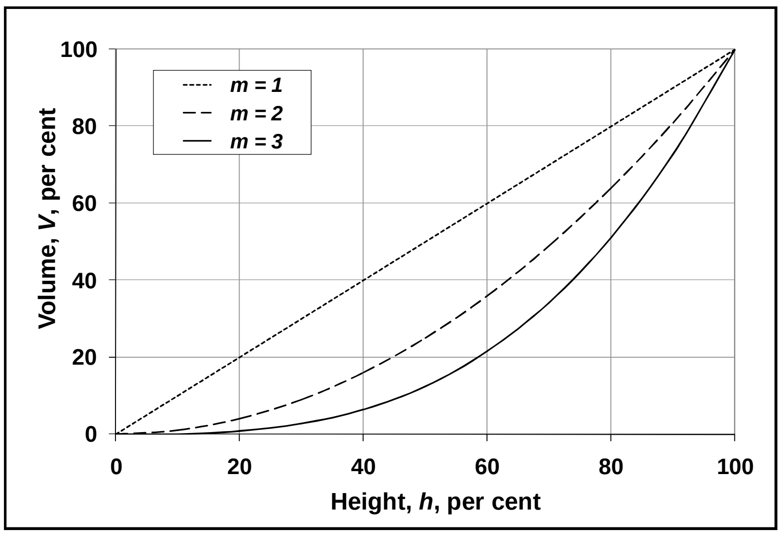

Figure 3.4. Per cent of dam height, h, versus per cent of volume, *V*, for dams of shape factors, *m* = 1, 2, and 3.

NWSB requires that reservoir storage be defined as a table or elevations and areas. The conversion from volume to area is

$$A = \frac{mV}{h} \tag{3.4}$$

where $A =$ reservoir surface area, ac.

Substituting the right-hand side of Equation 3.3 in to Equation 3.4 yields

$$A = \frac{m}{h}\beta h_d^{\alpha-m} h^m \tag{3.5}$$

Material rate parameters. In NWSB, D_{50} was selected as the varied parameter for altering erosion rate. As detailed in Chapter II, NWSB employs Smart's modification of the Meyer-Peter and Müller sediment transport relation (Fread 1991). While there appeared to be several candidate parameters for conducting material rate variations, it was shown that D_{50} had the largest impact on the sediment transport rate, Q_s. Also identified as important material parameters were internal friction angle, φ, and cohesive strength , C. However, because φ and C may have regions of insensitivity, or may affect Q_p either directly or inversely, they were eliminated from consideration. Also because D_{50} affects Q_s in Equation 2.1 in much the way that k_d controls $\dot{\varepsilon}$ in Equation 2.5, it is the best analog of SIMBA's erodibility coefficient, $k_{d,}$ in the context of the equation governing erosion. For SIMBA, the detachment/erodibility coefficient k_d, is the primary driver for predicting the rate of erosion. The values for the material rate parameters are determined as part of constructing a base case and corresponding baseline.

Base Case and Baseline Construction

Walder and O'Connor (1997) observed that the peak discharge Q_p is positively correlated to reservoir storage and shape factor. Because the SCS equation is an approximate upper envelope, it was expected that dams of high storage and possibly of high m would achieve the Q_p predicted by the SCS equation. Based on this expectation, a base case and baseline were established in this study from the highest storage curve, *UP*, and highest shape factor considered, $m = 3$.

As an initial step in conducting simulations and to observe coherence of the resulting breach peak discharge values with actual case histories, a base case was developed to match the peak discharge, $Q_{p,}$ determined from the SCS equation for a 50-ft high dam; the median of the heights modeled. For NWSB, the rate parameter value calculated for the base case was D_{50} = 5mm. Rate variation curves were established an order of magnitude above and below at D_{50} = 50mm and D_{50} = 0.5 mm. For SIMBA, the base erodibility was found to be k_d = 0.75 $ft^3\ lb^{-1}\ h^{-1}$. Rate variation curves above and below were calculated using k_d of 0.38 and 7.5 $ft^3\ lb^{-1}\ h^{-1}$. These values are summarized in Table 3.5.

From the base case, a baseline was established by varying h_d, while holding other parameters constant. Six other lines or curves were constructed by varying storage volume, reservoir shape, or the material rate parameter from the baseline. Therefore, none of the simulations differ from the base case in more than two parameters, one of them being height of dam, h_d.

Table 3.5 Material rate parameter values for the base line and for variations below the base (low), and above the base (high).

	model	NWSB	SIMBA
	rate parameter	D_{50} (mm)	k_d ($ft^3\ lb^{-1}\ h^{-1}$)
curve:	base	5	0.75
	low	50	0.38
	high	0.5	7.5

Consistency Challenges

NWSB required some additional inputs and workarounds to conduct the study. The first was inputs to determine tailwater influence. For the laboratory tests, these were estimated from knowledge of the test area and dimensions of the test embankments. For the synthetic set, a wide downstream cross section with a slope of 0.002 and n = 0.03 were entered to reduce its influence.

Secondly, NWSB does not allow the top width of the breach to erode beyond the distance entered for crest length. The ARS tests 1 and 2 were affected because these tests were initiated through a constructed channel or notch, but could widen farther during testing. This was also a significant limitation for modeling the synthetic data sets because the uniform discharge and drawdown requirements for breach initiation resulted in a set initial crest length. To overcome this, longer crest lengths were entered and the additional discharge was returned to the reservoir in the same time step by using an auxiliary spillway rating table with negative discharges equivalent to the flow through the added crest length. More details regarding this procedure and other intricacies in the operation of NWSB can be found in Appendix A.

CHAPTER IV

FINDINGS

ARS Test Data Sets 1 and 2

The measured discharge hydrographs and the NWSB and SIMBA predicted discharge hydrographs for the ARS tests 1 and 2 are compared in Figures 4.1 and 4.2, respectively. For ARS tests 1 and 2, NWSB predicted a near instantaneous breach once the reservoir filled and began to overtop. While the NWSB predictions for timing and discharge are less than perfect for test 1, the event does take place fairly quickly and in the realm of embankment breach predictions, peak discharge estimates within the same order of magnitude are laudable. However test 2 shows that NWSB is unable to account for the cohesive behavior of the soils. This embankment withstood nearly a full day of overtopping without eroding through the crest. NWSB looks at this well-constructed, clay embankment as a pile of fine non-cohesive material. SIMBA on the other hand, based on measured material parameters, was able to predict both events well. Its use of an erodibility rate allows it to account for the behavior of the soils. These results have important implications and raise the question of what impact key parameters may have on breach discharge values and what information can be gleaned from a parametric study of synthetic data sets.

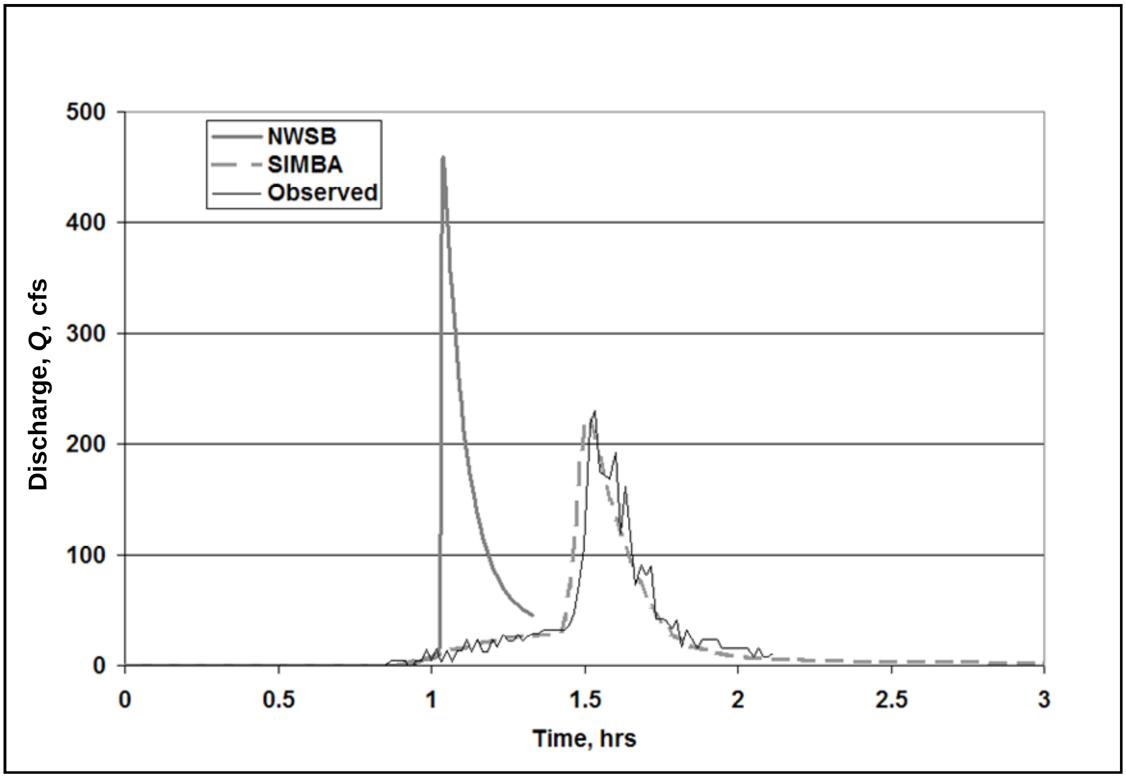

Figure 4.1 Discharge hydrograph for overtopping test 1 showing NWSB and SIMBA predictions against observed values.

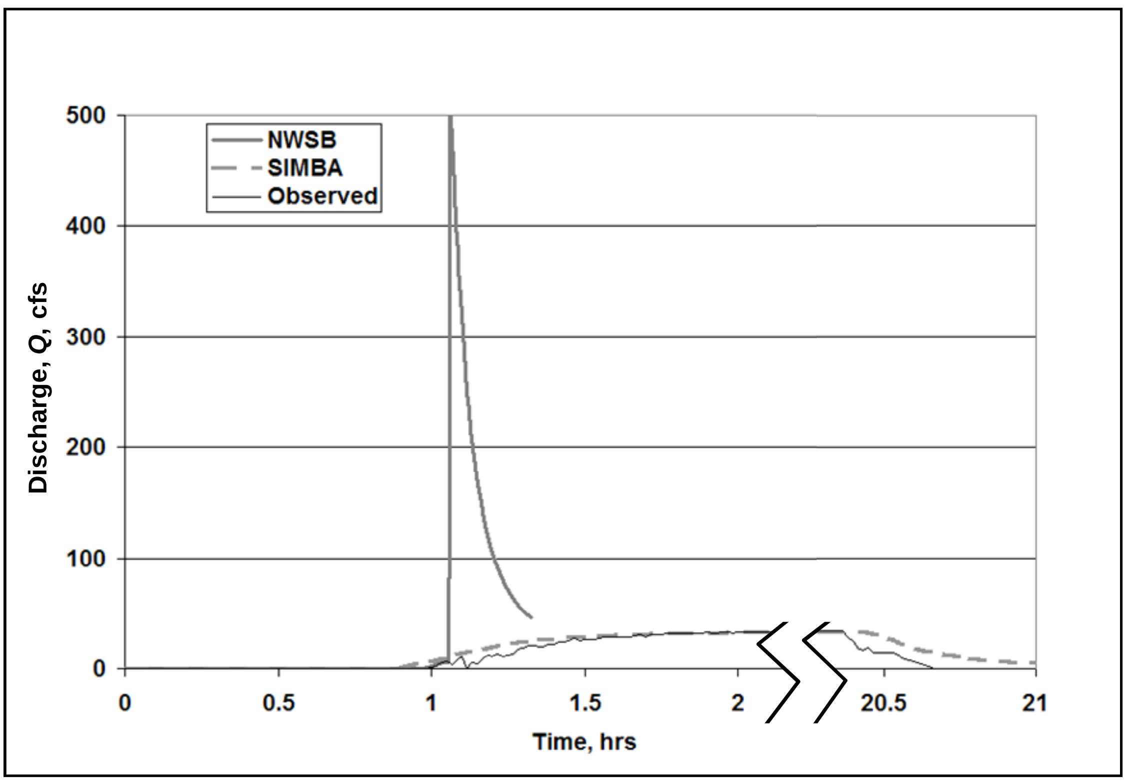

Figure 4.2 Discharge hydrograph for overtopping test 2 showing NWSB and SIMBA predictions against observed values.

Synthetic Data Sets

As explained in Chapter 3, the synthetic data sets were established by initially developing a single base case dam that was calibrated to match the Q_p value predicted from the SCS equation. The base case dam was set with an h_d = 50 ft, V_s = 89,600 ac ft (from the *UP* storage curve), and having shape factor m = 3. The key material rate parameter D_{50} for NWSB and k_d for SIMBA was adjusted to produce the matching Q_p = 90,000 cfs for both models. The resulting breach discharge hydrographs are plotted in Figure 4.3. While the peak discharge output for the NWSB and SIMBA models are similar, the hydrograph timing and material parameters used to match the Q_p were quite different. NWSB's base case material was; D_{50} = 5mm, D_{90}/D_{30} = 10, φ = 32°, and C = 250 lb ft^{-2}, which would be properties similar to a weak, moderately graded, gravel. SIMBA's base case material was; k_d = 0.75 ft^3 lb^{-1} h^{-1} and C_u = 1000 lb ft^{-2}, which would be properties similar to a cohesive, medium consistency, moderately erodible soil.

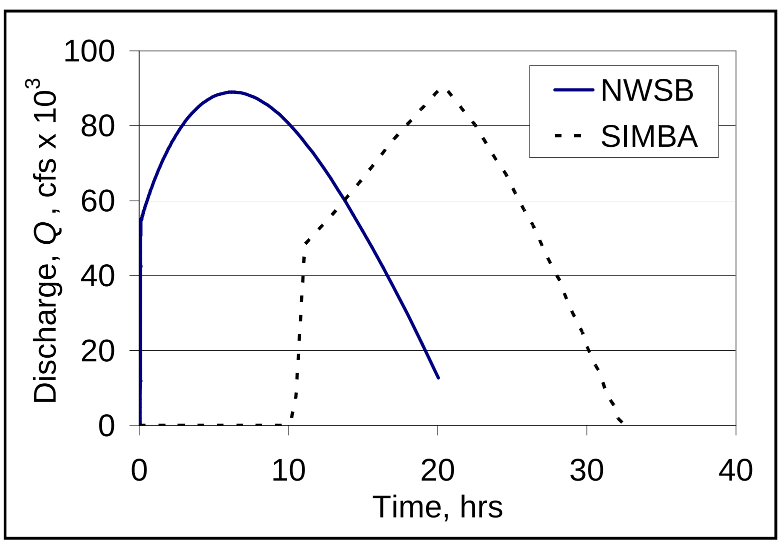

Figure 4.3 Breach discharge hydrographs for the base cases NWSB and SIMBA, where h_d = 50 ft, Storage *UP*, m = 3, D_{50} = 5mm (NWSB), k_d = 0.75 ft^3 lb^{-1} hr^{-1} (SIMBA).

Once the base case was established for each model, overtopping breach simulations of synthetic dam data sets were conducted. Results are presented in the following order:

1) Variation of h_d and the corresponding V_s for the *UP* storage curve with $m = 3$, $D_{50} = 5$mm, and $k_d = 0.75$ ft^3 lb^{-1} h^{-1} (baseline),
2) Variation of h_d and the corresponding V_s for the *R* and *LP* storage curves with $m = 3$, $D_{50} = 5$ mm, and $k_d = 0.75$ ft^3 lb^{-1} h^{-1} ,
3) Variation of h_d, shape $m = 2$ and 1, and the corresponding V_s for the *UP* storage curve, $D_{50} = 5$ mm, and $k_d = 0.75$ ft^3 lb^{-1} h^{-1}, and
4) Variation of h_d, $D_{50} = 0.5$ mm and 50 mm, and $k_d = 0.38$ ft^3 lb^{-1} h^{-1} and 7.5 ft^3 lb^{-1} h^{-1} and the corresponding V_s for the *UP* storage curve.

The Q_p prediction results are reported in tables 4.1 (NWSB) and 4.2 (SIMBA). The Q_p values are strictly for flow through the breach. In some cases, especially NWSB, the peak breach discharge occurred while the dam was being overtopped. Because the one foot of overtopping and crest length commensurate to storage were merely a convention for initiating the breach, the overtopping discharge is not considered. That being said, breach discharge is not defined identically for NWSB and SIMBA. NWSB considers only the flow through the cross sectional area of the breach below the crest elevation, while SIMBA reports all flow through the computed width of the breach to be breach discharge. The maximum difference is 3 cfs unit discharge. In most cases this was insignificant.

Table 4.1. Peak breach discharge, Q_p, for the synthetic dams set as predicted by the SCS equation and NWSB.

	SCS equation	NWSB Synthetic Dams						
			Varied parameter					
		Set 1 baseline	Set 2 Storage		Set 3 *m*		Set 4 D_{50}	
Storage	-	*UP*	*R*	*LP*	*UP*	*UP*	*UP*	*UP*
Shape, *m*	-	3	3	3	2	1	3	3
D_{50}, mm	-	5	5	5	5	5	0.5	50
h_d, ft	Q_p, cfs							
5	1.28×10^3	5.6×10^2	3.0×10^2	2.7×10^2	5.6×10^2	5.6×10^2	5.4×10^2	5.0×10^2
10	4.6×10^3	1.47×10^3	1.46×10^3	1.28×10^3	1.4×10^3	1.48×10^3	1.47×10^3	1.47×10^3
20	1.66×10^4	7.7×10^3	7.6×10^3	5.8×10^3	7.7×10^3	7.7×10^3	7.7×10^3	1.07×10^4
50	9.0×10^4	8.8×10^4	5.4×10^4	2.7×10^4	7.9×10^4	6.6×10^4	7.3×10^4	1.32×10^5
100	3.2×10^5	3.8×10^5	2.8×10^5	5.7×10^4	3.5×10^5	3.1×10^5	3.3×10^5	5.4×10^5
200	1.17×10^6	1.54×10^6	1.25×10^6	1.16×10^5	1.46×10^6	1.42×10^6	1.45×10^6	2.1×10^6
400	4.2×10^6	9.1×10^6	6.7×10^6	2.1×10^5	9.0×10^6	8.8×10^6	9.1×10^6	9.6×10^6

Table 4.2 Peak Discharge, Q_p, for the synthetic dams set as predicted by the SCS equation and SIMBA.

	SCS equation	SIMBA Synthetic Dams						
			Varied parameter					
		Set 1 baseline	Set 2 Storage		Set 3 *m*		Set 4 k_d	
Storage	-	*UP*	*R*	*LP*	*UP*	*UP*	*UP*	*UP*
Shape, *m*	-	3	3	3	2	1	3	3
k_d, ft^3 lb^{-1} hr^{-1}	-	0.75	0.75	0.75	0.75	0.75	0.38	7.5
h_d, ft	Q_p, cfs							
5	1.28×10^3	5.4×10^2	6×10^0	1×10^0	4.7×10^2	3.9×10^2		1.93×10^3
10	4.6×10^3	2.4×10^3	4.5×10^1	1×10^0	2.2×10^3	1.84×10^3		7.1×10^3
20	1.66×10^4	1.15×10^4	8.5×10^2	2×10^0	1.06×10^4	8.5×10^3		2.8×10^4
50	9.0×10^4	9.0×10^4	3.6×10^4	2.5×10^2	7.7×10^4	5.3×10^4	5.7×10^4	1.89×10^5
100	3.3×10^5	3.4×10^5	1.46×10^5	6.8×10^2	2.9×10^5	2.7×10^5	2.6×10^5	8.4×10^5
200	1.18×10^6	1.60×10^6	4.3×10^6	1.75×10^3	1.57×10^6	1.58×10^6	1.59×10^6	4.3×10^6
400	4.2×10^6	9.5×10^6	1.30×10^7	4.5×10^3	9.3×10^6	9.3×10^6	9.1×10^6	2.2×10^7

Synthetic Set 1 - Baseline

The baseline case, set 1, for the NWSB and SIMBA Q_p results were quite similar and as expected, predicted Q_p increased with increasing height and storage for both models (Figure 4.4). Less expected was that the results for both models were quite similar to the SCS equation even though h_d = 50 ft was the only point calibrated. This result by itself is intriguing in both cases. The results were slightly steeper in log-log space than the SCS equation, with the Q_p ranging from about 40% of the SCS equation at h_d = 5 ft to a little more than 200% of the SCS equation at h_d = 400 ft. For the baselines, dam height is varied and with it storage as defined by the *UP* curve.

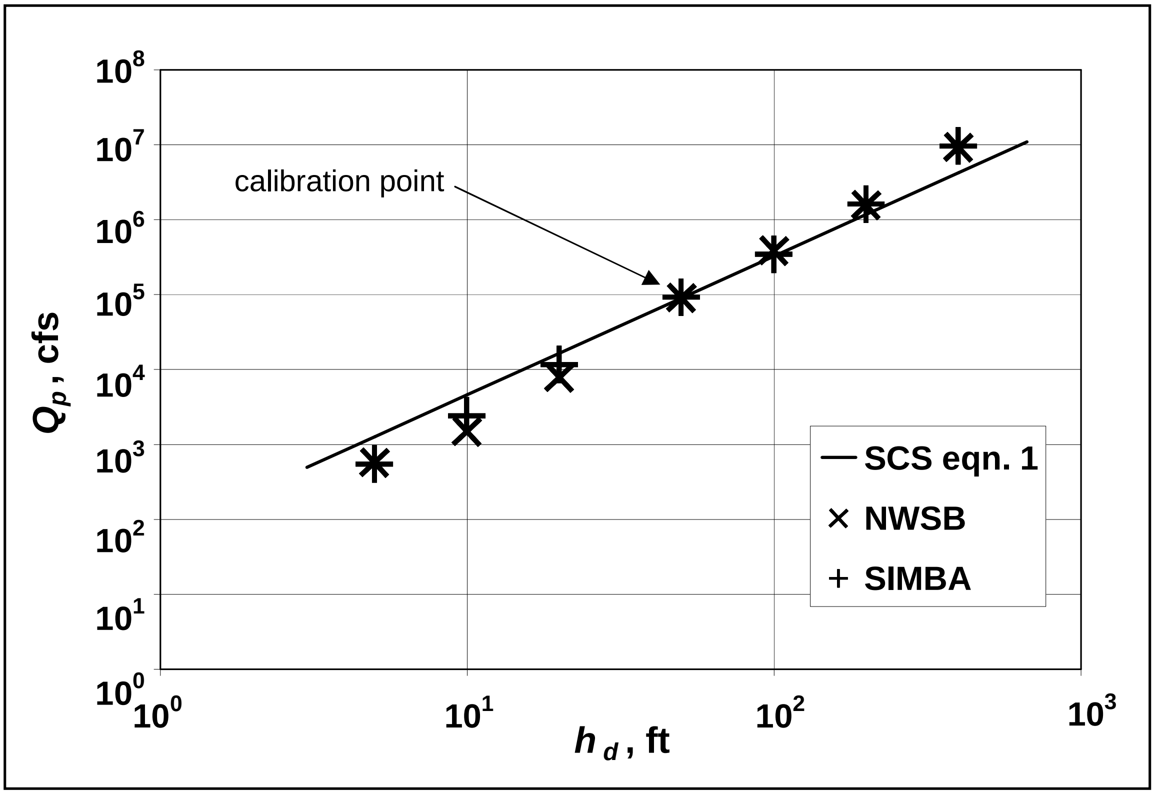

Figure 4.4 Peak breach discharge, Q_p,versus dam height, h_d, as predicted by the SCS equation and for the synthetic dams set baselines by NWSB, and SIMBA. Calibration point is indicated for h_d = 50ft. For the baselines storage volume is defined by the upper prediction (*UP*) envelope, shape m = 3, and material rate parameters D_{50} = 5mm (NWSB) and k_d = 0.75 ft^3 lb^{-1} hr^{-1} (SIMBA).

Synthetic Set 2 - Storage, V_s

Both models were visibly responsive to the storage curve variations as shown in Figure 4.5. This was less pronounced for NWSB, because the peak discharge tended to occur very quickly, in less than one hour, for many of the dams, when most of the reservoir head and volume were still available. The peak discharges of the *R*-sized reservoirs fell within the same order of magnitude as the *UP* reservoirs, generally about one-fourth reduction. Simulations on the *LP* curve produced reductions at or near an order of magnitude for dams of $h_d \geq 50$ ft, which was quite surprising and difficult to explain. For dams of $h_d \leq 20$ ft, the average reduction was 30% relative to *UP*.

SIMBA showed marked response to each successive reduction in storage, one to two orders of magnitude for much of the *R* curve. Reductions on the *LP* curve were in most cases in excess of three orders of magnitude and for $h_d < 50$ Q_p was only 1 or 2 cfs. These extremely low predictions may warrant further investigation regarding operation of the model. However the trend of the series suggests these values should be very low. These results also point out the potential importance of properly accounting for the reservoir storage relative to peak breach discharges.

A discontinuity appears in the range of dam heights of $20 < h_d < 50$ ft. While present to some degree in many of the series, it is perhaps best highlighted in the storage curve variations. This can likely be attributed to height-dependent processes. In NWSB, slope failure requires some minimum height relative to the strength parameter entries. In SIMBA overfall height and headcut advancement are positively correlated.

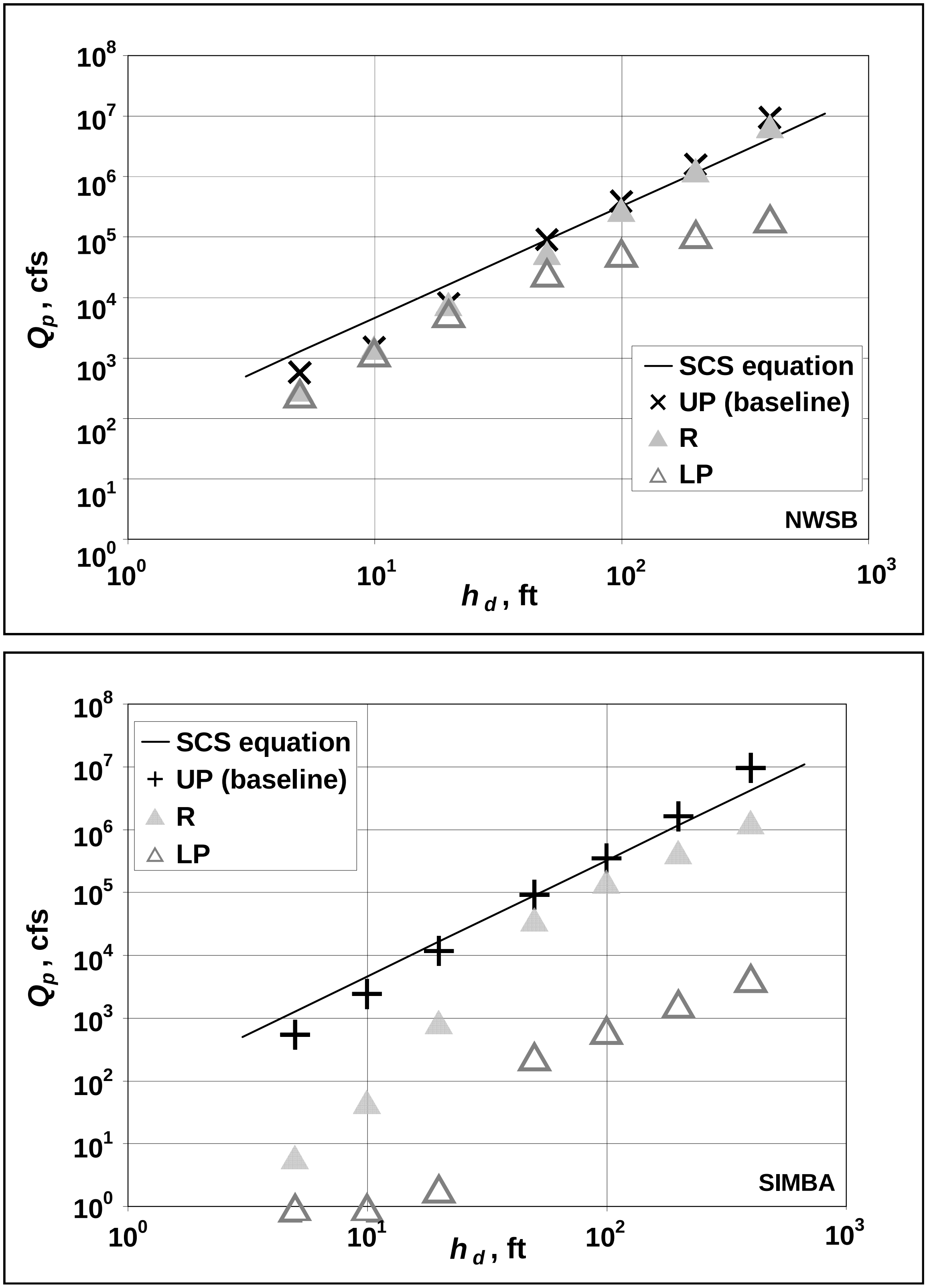

Figure 4.5 Peak breach discharge, Q_p, versus dam height, h_d, as predicted by the SCS equation and for the synthetic dams set baselines and variations of storage volume regression, *R*, and lower prediction curve, *LP*, by NWSB (top) and SIMBA (bottom).

Sensitivity to the changes in storage were to be expected as the range of the storage curves is three orders of magnitude, and Walder and O'Connor (1997) found storage with erosion rate to produce the best estimates of probable breach discharge. It causes some concern that NWSB is not more sensitive than demonstrated here.

Synthetic Set 3 – Shape, m

Neither model was visibly responsive to the storage shape factor as shown in Table 4.1 and 4.2 and the plots of Figure 4.6. This was initially surprising but may have as much to do with the material properties used and the resulting relatively rapid rate of breach formation for both models. In the scenario of a rapid breach formation, the primary driver for Q_p would be the full head of the reservoir upstream. In the scenario of a slow breach formation, the reservoir level lowering may occur during formation and shape may have more of an influence. Interestingly, NWSB showed no response to changes in shape when $h_d < 50$, experienced slight reductions relative to the baseline at $h_d = 50$, and diminished to almost no response at $h_d = 400$ ft. While a large dependence on shape is not expected, the near absence of influence can be attributed to the tendency of NWSB to predict peak discharge very quickly, as was the case for storage.

While dependence on shape was also minor for SIMBA, Q_p generally behaved more consistently. Shape variations had a greater effect on shorter dams than on taller structures. There was essentially no effect for dams of $h_d \geq 200$ ft, but below that value its influence increased with decreasing h_d. At $h_d = 5$ ft, $m = 2$, the reduction in Q_p was 20% relative to $m = 3$. At $m = 1$, the reduction was nearly 30%.

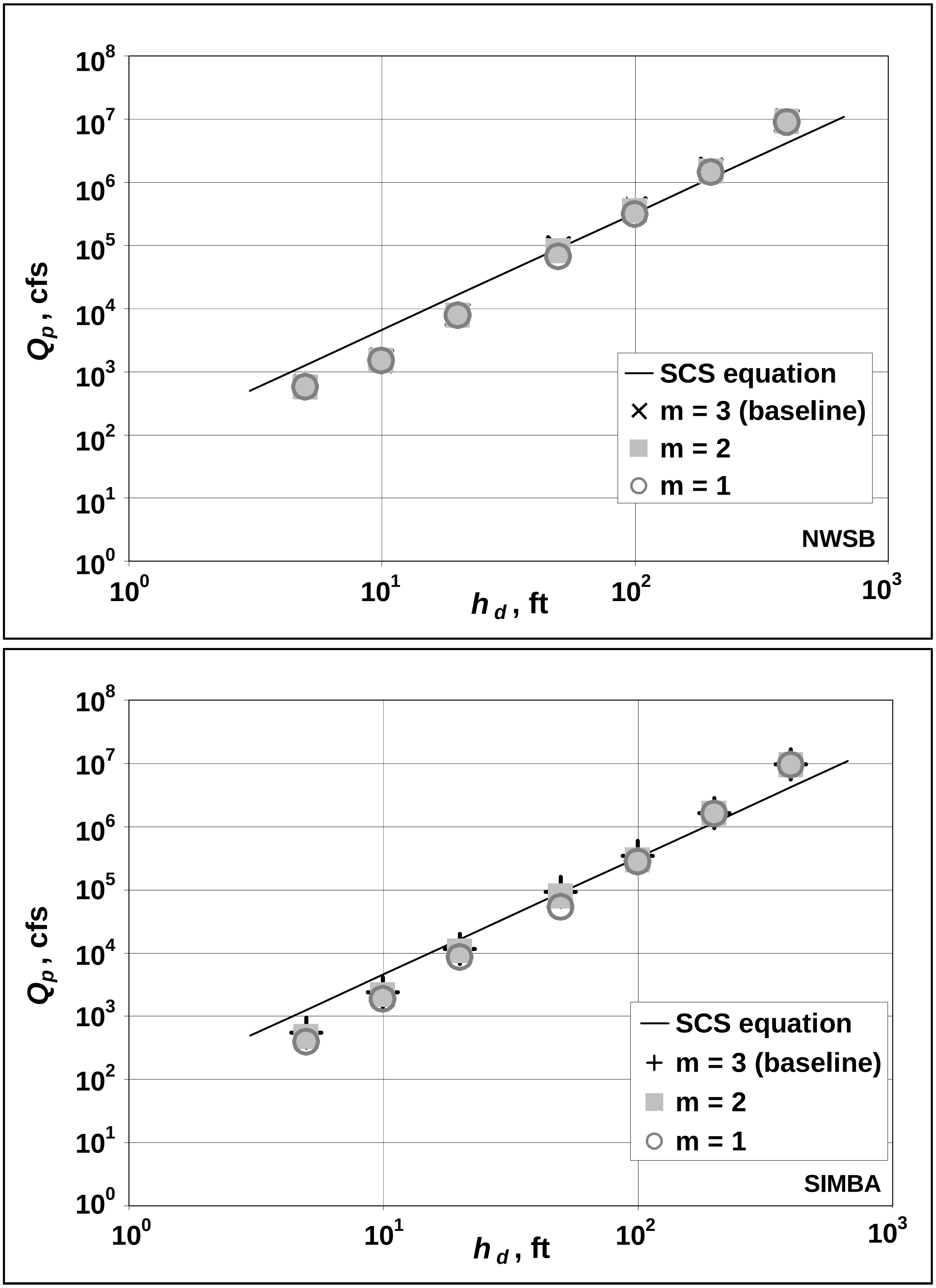

Figure 4.6 Peak breach discharge, Q_p, versus dam height, h_d, as predicted by the SCS equation and for the synthetic dams set baselines and variations of reservoir shape, *m*, by NWSB (top) and SIMBA (bottom).

Synthetic Set 4 - Material Parameter, D_{50} (NWSB) and k_d (SIMBA)

NWSB was not visibly responsive to a two order magnitude variation in D_{50}. The variation that was observed was for the intermediate dam heights with virtually no effect on the largest and smallest heights (Table 4.1, Figure 4.7). The effect was opposed to what would be expected intuitively. The largest material, D_{50} = 50 mm, resulted in roughly a 50% increase in Q_p for the intermediate heights. The smallest material, D_{50} = 0.5 mm, resulted in a 10 to 20% reduction of Q_p for the intermediate heights.

SIMBA results showed marked response to variations in k_d (Table 4.2, Figure 4.6): two to three times increase in Q_p for an order magnitude increase in k_d and no breach failure for h_d < 50 ft for a 50% reduction in k_d. These results point out the potential importance of properly accounting for material properties and erosion process.

Altering D_{50} in NWSB had less effect than expected and was confined to a central range of dam heights. More importantly, the behavior of Q_p tends to be opposite that which was expected. It was thought that Q_p would decrease with increasing D_{50}. As compared to the baseline, the opposite was true for nine cases, while no change occurred in four. Only for the smallest dam with D_{50} = 50 mm, was the response in the expected direction.

For SIMBA, the response to changes in erodibility, k_d, were largely as expected. Increasing k_d tended to lead to increases in Q_p. Relative to the baseline, the lower rate, k_d = 0.38 $ft^3\ lb^{-1}\ hr^{-1}$, had little effect on Q_p for dams of 200 ft and above. However Q_p is cut nearly in half for the 50-ft dam. The most dramatic effect is for dams of less than 50 ft in height; SIMBA predicted no breach would occur. Note that this lower rate is only a

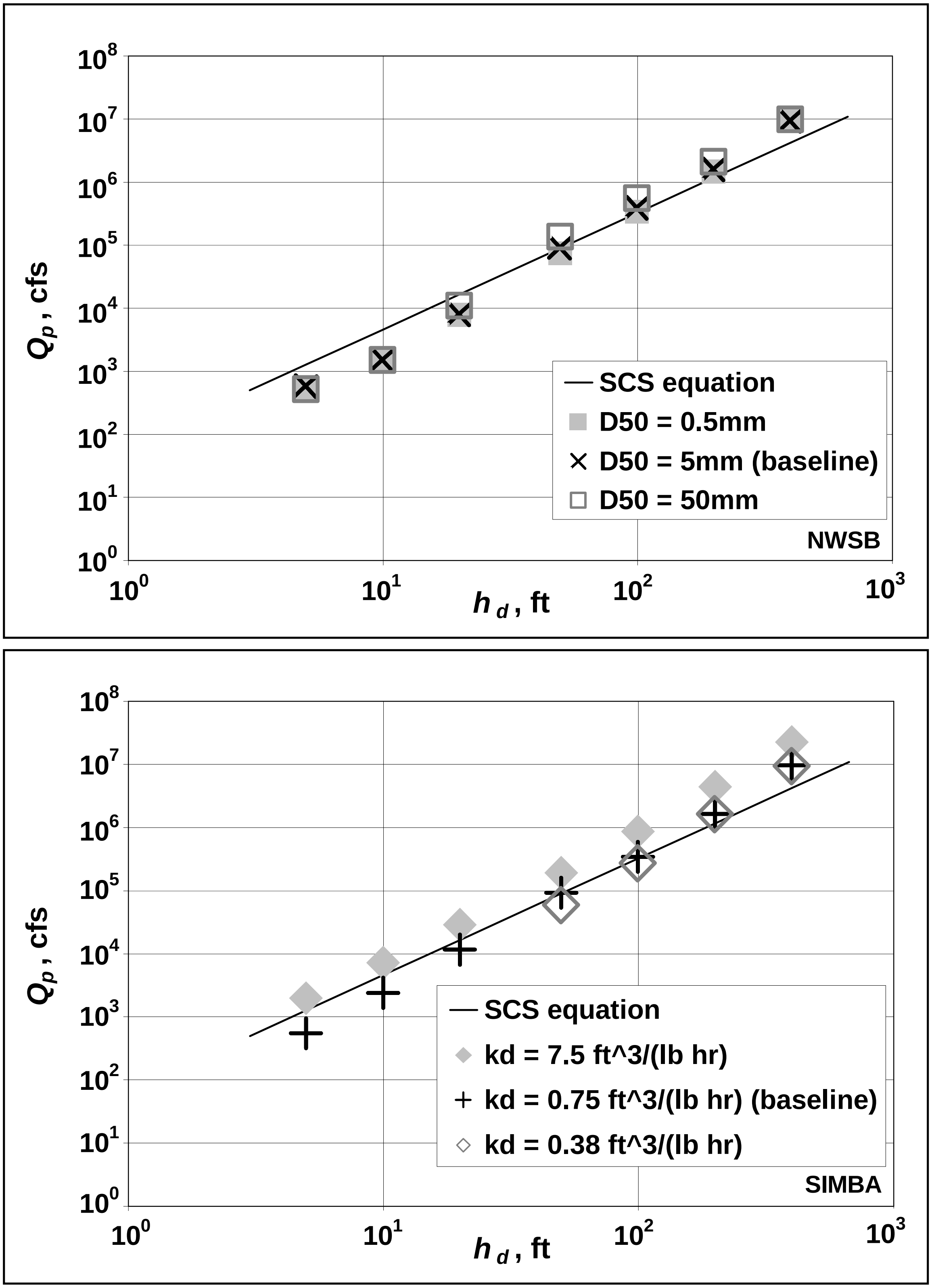

Figure 4.7 Peak breach discharge, Q_p, versus dam height, h_d, as predicted by the SCS equation and for the synthetic dams set baselines and variations of median particle size diameter, D_{50}, by NWSB (top) and variations of erodibility, k_d, by SIMBA (bottom).

one-half reduction of the baseline erodibility. It had been desired to do a full order of magnitude reduction, but no dams of any height were predicted to breach. The upper rate was carried out at an order of magnitude above that of the baseline, $k_d = 7.5$ ft^3 lb^{-1} hr^{-1}. Relative to the baseline, Q_p was increased by about 2 to 3×, with the higher dams seeing less increase than smaller dams.

CHAPTER V

SUMMARY AND CONCLUSIONS

Prediction of the peak discharge and outflow hydrograph from a dam breach is an important component in evaluating risk to life and property downstream of a dam. Evaluation of risk downstream is also important in prioritizing distribution of limited public and private funds for rehabilitation of the aging dams across the United States. Historical dam failures have played an important role in the development of methods for predicting peak discharge and outflow hydrographs for a dam failure but the methods developed do have recognized shortcomings. Historical failure data and the tools developed from them; 1) do not necessarily represent existing dams on the NID; 2) are highly uncertain (Wahl 2004, Wahl 1998); 3) assume a dam failure will occur, and 4) neglect breach failure processes and impact of embankment materials.

Process based computational breach models are another tool and do not assume a dam will fail when overtopped and allow the user to evaluate the impact of failure processes, embankment materials, surface conditions, embankment geometry, reservoir storage and shape. Two process based computation breach models were used in this study; NWSB and SIMBA. The two models assume very different erosion equations and processes. NWSB uses the Meyer-Peter and Müller sediment transport equation as modified by Smart and assumes the erosion process is uniformly driven. SIMBA uses the excess stress equation and assumes the erosion process is a discontinuity headcut driven model.

ARS Test Data Sets 1 and 2

Two physical model tests, ARS tests 1 and 2, were evaluated using the two process based computation models, NWSB and SIMBA. NWSB predicted a greater peak breach discharge and more rapid hydrograph development than what was observed for test cases 1 and 2. SIMBA predicted peak breach discharges and hydrographs that were in direct alignment with what was observed for both cases.   The results from the two computational models point out the difference in the models and the potential importance of properly modeling the processes involved. The results also point out that individual characteristics and evaluation of these characteristics is important in determining how a dam may perform.   This is an important concept when faced with hard decisions relative to prioritizing distribution of funds for rehabilitation.

Synthetic Data Sets

NWSB and SIMBA were used to evaluate impact of parameter variations on predicted breach peak discharge, Q_p for a series of synthetic data set of dams over the range of dams found in the historical failure record. The parameters evaluated were dam height, reservoir storage volume, reservoir storage shape, and a key material parameter. Synthetic data sets hinged upon construction of the initial base case. The base case was developed for a dam height of 50 ft, storage volume at the upper 95% prediction interval of historical dam failure cases, storage shape factor of 3, and a material parameter that resulted in a Q_p matching that predicted by the SCS equation. There are likely other scenarios for which the prediction of the SCS equation could have been matched but this provided a beginning point for evaluating impact of parameter variations.

For NWSB a contradiction seems to exist between the experience of setting up the base case and for ARS test 2. It took several iterations to settle upon a set of parameter values that would produce a Q_p matching the SCS equation for the base case as early attempts were consistently low. Material strength parameters had to be adjusted lower (φ = 32°, C = 250 lb ft^{-2}) until widening occurred that was adequate to produce the desired discharge. It suggests that a poorly constructed embankment is needed to match the equation. For laboratory breach test 2, essentially the opposite was observed. There was no way to appropriately model this well-constructed embankment, resulting in gross over prediction of peak discharge.

In SIMBA's case, the materials that could match the equation are perhaps more erodible than ideal, but not to the point that you would never expect to find them in an engineered embankment. The erodibility, k_d = 0.75 ft^3 lb^{-1} hr^{-1}, is considered moderate, and C_u = 1000 lb ft^{-2} is competent material. These values fell directly between the measured values of ARS tests 1 and 2. Laboratory breach tests highlight a real danger within NWSB, as it requires inputs that are easily obtained or estimated within reason. Modelers may acquire a false sense that because the model has been provided reliable information, it will produce reliable results. However, the information is not necessarily adequate to appropriately model the process of dam breach.

The next step in evaluation of parametric impact was variation of h_d relative to the base case. This resulted in Q_p values very similar to the SCS equation for both NWSB and SIMBA. The similarities of slopes in the Q_p versus h_d of this baseline scenario for both models and the SCS equation were observed with great interest. Because the models were observed to be very sensitive to storage, the resulting slope of the baselines is really a function of the slope of the storage curve. While the historical dam failures used to develop the SCS equation are only a subset of those used to produce the storage curves, it suggests the SCS equation appropriately follows the tendencies of the larger data set of historical dam failures. With the exception of h_d and the lowest storage curve for large h_d values, NWSB Q_p predictions were observed to be relatively insensitive to changes in parameter values. It was concluded based on observations from results of ARS test cases 1 and 2 and the synthetic runs, that this was due to the rapid rate of breach predicted by NWSB. Rapid breach formation rates result in small changes in reservoir elevation at full breach formation which in turn results in Q_p values dependent on the initial reservoir elevation. The only scenario that would possibly not follow this would be the case of tall dams with small storage which, as mentioned above, is what was observed.

SIMBA Q_p predictions, on the other hand were observed to be sensitive to parametric variations with the exception of storage shape. This was true for all h_d but particularly true of $h_d < 50$ ft. Q_p was observed to be dramatically affected by relatively small storage and low erodibility values. This potentially has important implications when evaluating risk and rehabilitation needs.

SIMBA does face a hurdle as it requires the user to define erodibility. Tests of erodibility are not widely conducted, making its most crucial input more difficult to obtain. Modelers have less experience with this parameter and will be less likely to have confidence in its estimation. An additional observation is that both models require entry of stage-storage tables to operate. Although this information is not included in large databases such as the National Inventory of Dams (USACE 2005), results from this study indicate that reservoir stage-storage shape may not be an important factor. This will have to be more thoroughly investigated with a more extensive parametric study.

In addition to limitations and challenges facing the models listed above, it is appropriate to mention that a model is a simplification. The processes of dam breach are not fully understood. Furthermore the synthetic set of dams was itself a model, calibrated against the SCS equation, which is yet another model. The procedure relied upon many simplifications, such as changing erodibility or median soil particle size without altering other material properties. It is understood that dependencies exist between many of the inputs, but these factors were beyond the scope of the study.

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APPENDIX A

NATIONAL WEATHER SERVICE BREACH

NWSB confronted the author with additional challenges. While some of these were deemed worthy of noting earlier, others are detailed here to assist the reader in using NWSB.

Circumventing Dam Crest Length Limit

As mentioned at the close of Chapter III, NWSB does not allow a breach to widen beyond the initial crest length, L_C. For most dams, this is not an issue as their crests are of sufficient length that the final breach width is limited by other factors. Still in other instances, a modeler might enter a crest length greater than the actual without introducing significant errors, e.g. for overtopping of a minimal depth or where downstream valley geometry limits the peak discharge.

This actually presented a significant challenge at first and required creative experimentation with NWSB until a workable solution was developed. To circumvent this, a larger value can be entered for L_C, and the extra discharge can be offset using a negative spillway discharge table corresponding to the extraneous length of crest, which is the spillway length, L_{SP}.

This approach produced no appreciable error as long as the reservoir water surface elevation was below the crest elevation at or before the time at which the breach widens beyond the actual crest length being modeled. For cases where the water surface elevation remained above the crest elevation at the time of peak discharge and which had the potential to widen beyond initial crest length, the crest length was adjusted to be no more than 1 ft greater than the top width of the breach at the time of peak discharge. The method is depicted in Figure A.1.

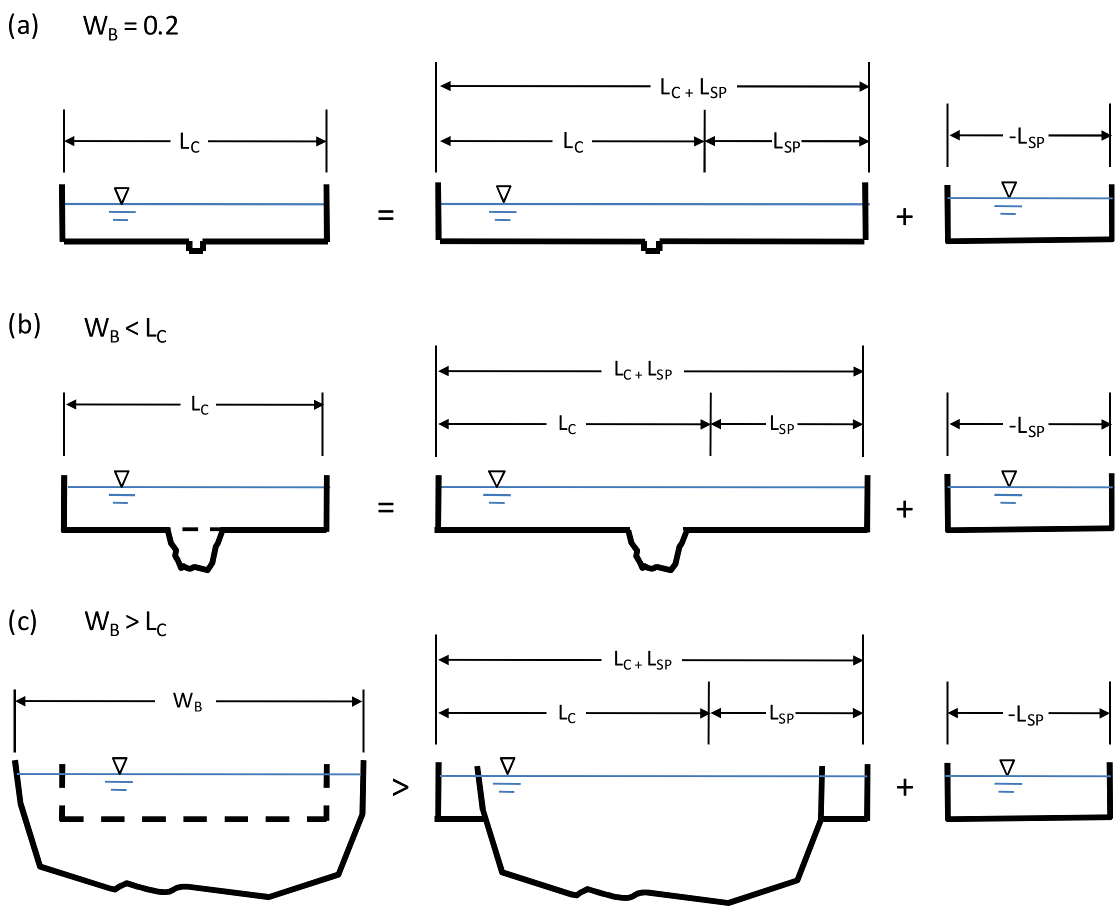

Figure A.1. Conceptualized sequence of breach width, W_B, developing beyond dam crest length, L_C. A false crest length offset by a negative spillway discharge table was used to offset the additional "spillway" length, L_{SP}. (a) Breach flow in NWSB initiates through a predefined channel on dam face, usually 0.2ft wide. (b) It widens and deepens. (c) If it widens beyond the actual crest length, the breach width can be greater than the combined entered crest length and negative spillway.

NWSB requires non-zero hydrograph

NWSB did not successfully execute if a hydrograph table of zero flow rate was entered. Until discovered, this behavior caused the author considerable difficulty in trying to conduct the synthetic data sets runs. Once discovered, a small base flow of 1 cfs was used to satisfy this requirement.

NWSB Breach Bottom Width Error

Documentation for NWSB (Fread 1991) states that for non-entry of the maximum allowable breach bottom width, BMX, the parameters value will default to entered crest length, CRL. The observed behavior of the model was contrary to this statement. Non-entry of BMX produced readily discernable errors, e.g. negative values, which prevented model from executing a full run. In all cases the problem was corrected by entering BMX = CRL.

APPENDIX B

ARS TEST 1 EXPERIMENT SUMMARY

AND MODEL FILES

Table B.1. ARS test 1 physical dimensions.

Embankment Dimensions	
Height of Embankment	7.3 ft
Elevation of Embankment	107.3 ft
Top Length	24 ft
Top Width	6 ft
Upstream Slope	3/1 (H/V)
Downstream Slope	3/1 (H/V)
Elevation @ Base	100 ft
Embankment Width @ Toe	50 ft
Test Section Dimensions	
Height of Test Section	5.8 ft
Notch Base width	6.0 ft
Notch Side Slopes	3/1 (H/V)
Notch Depth	1.5 ft
Crest Width @ Notch	15 ft
Elevation of Crest	105.8 ft

Figure B.1. ARS Test 1 embankment before overtopping experiment.

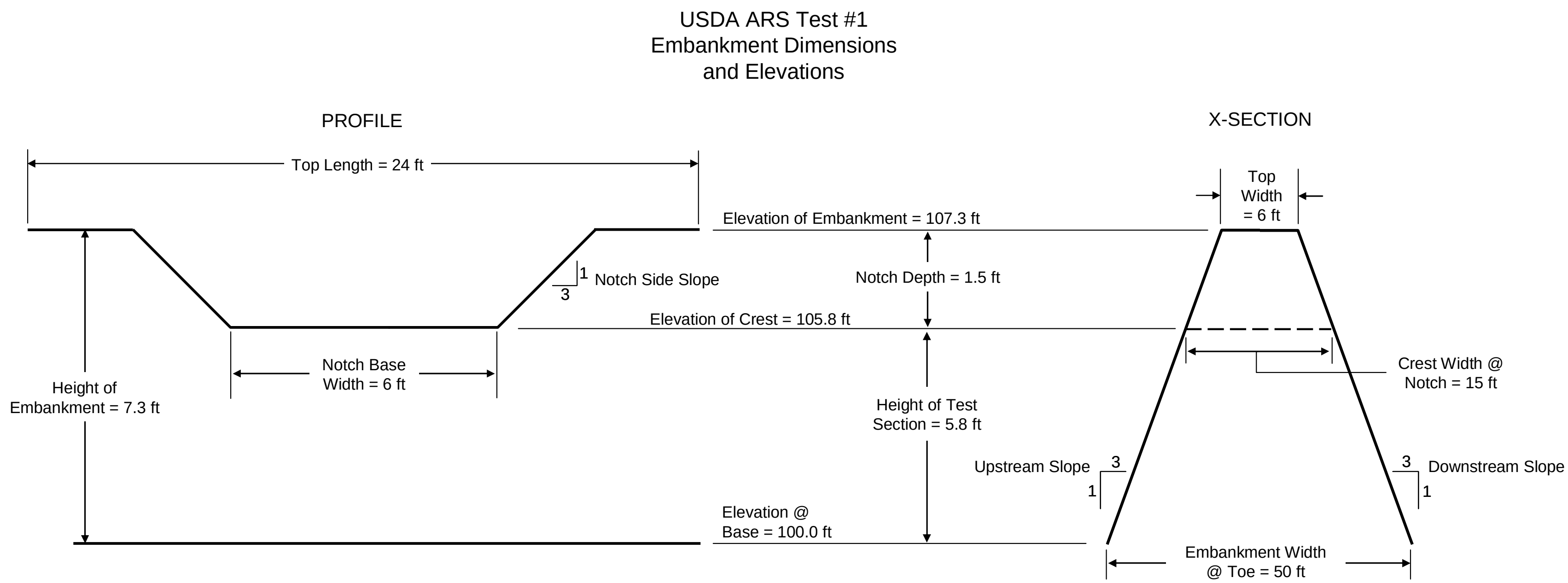

Figure B.2. As-built profile and cross section of ARS test 1 embankment.

Table B.2. Summary of soil analysis for ARS test 1.

Gradation		
% Clay < 0.002 mm		5
% Silt > 0.002 mm		25
% Sand > 0.105 mm		70
Plasticity Index	Non-plastic	
USCS	SM	
Grain Density g/cm^3		2.67
Unconfined Compressive Strength q_u (lb/ft^2)		425
Average Dry Density (lb/ft^3)		107.05
Average Water Content @ construction %		8.9
Average Total Density (lb/ft^3)		116.6
porosity		0.30
Erodibility Coefficient kd (ft/h)/(lb/ft^2)		5.77
Critical stress τ_c lb/ft^2		0
Construction		
Compaction Effort	~4000 ft-lb/ft^3	
Loose Lift Thickness	0.5 ft	
Compacted lift thickness	0.4 ft	
Constructed 9/1998		

Seive Analysis	mm	% Finer
0.002 mm	0.002	5
0.005 mm	0.005	7
# 200 (0.075 mm)	0.075	30
# 140 (0.106 mm)	0.106	39
# 60 (0.250 mm)	0.25	71
# 40 (0.425 mm)	0.425	93
# 20 (0.850 mm)	0.85	99
# 10 (2.00 mm)	2	100

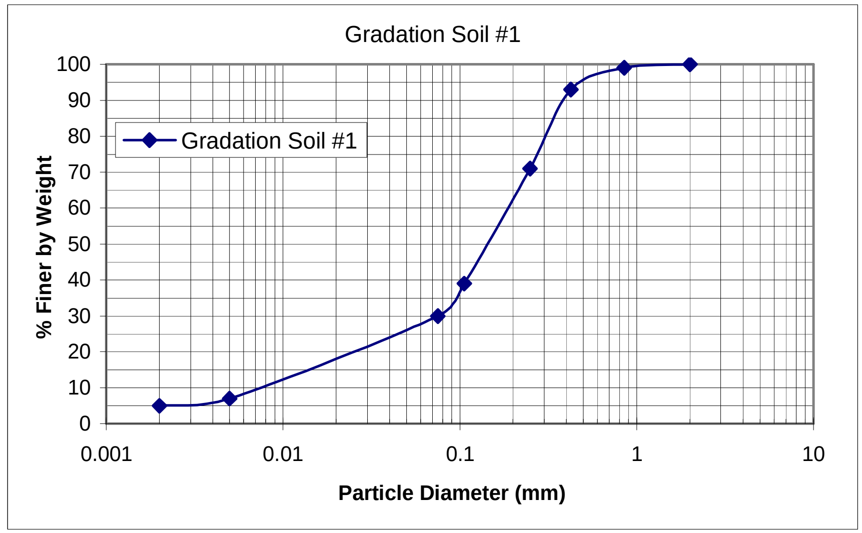

Figure B3. Plot of particle sized distribution of embankment material for ARS test 1.

Table B.3. Elevation versus volume for reservoir used in ARS tests 1 and 2.

Elevation	H	Δ Volume ft^3	Volume ft^3
100.0	0.0		0
100.5	0.5	5837	5837
101.0	1.0	7754	13591
101.5	1.5	9278	22869
102.0	2.0	10454	33323
102.5	2.5	11326	44649
103.0	3.0	11979	56628
103.5	3.5	12458	69086
104.0	4.0	12807	81893
104.5	4.5	13155	95048
105.0	5.0	13504	108552
105.5	5.5	13939	122491
106.0	6.0	14462	136953
106.5	6.5	15245	152198
107.0	7.0	16292	168490
107.5	7.5	17598	186088

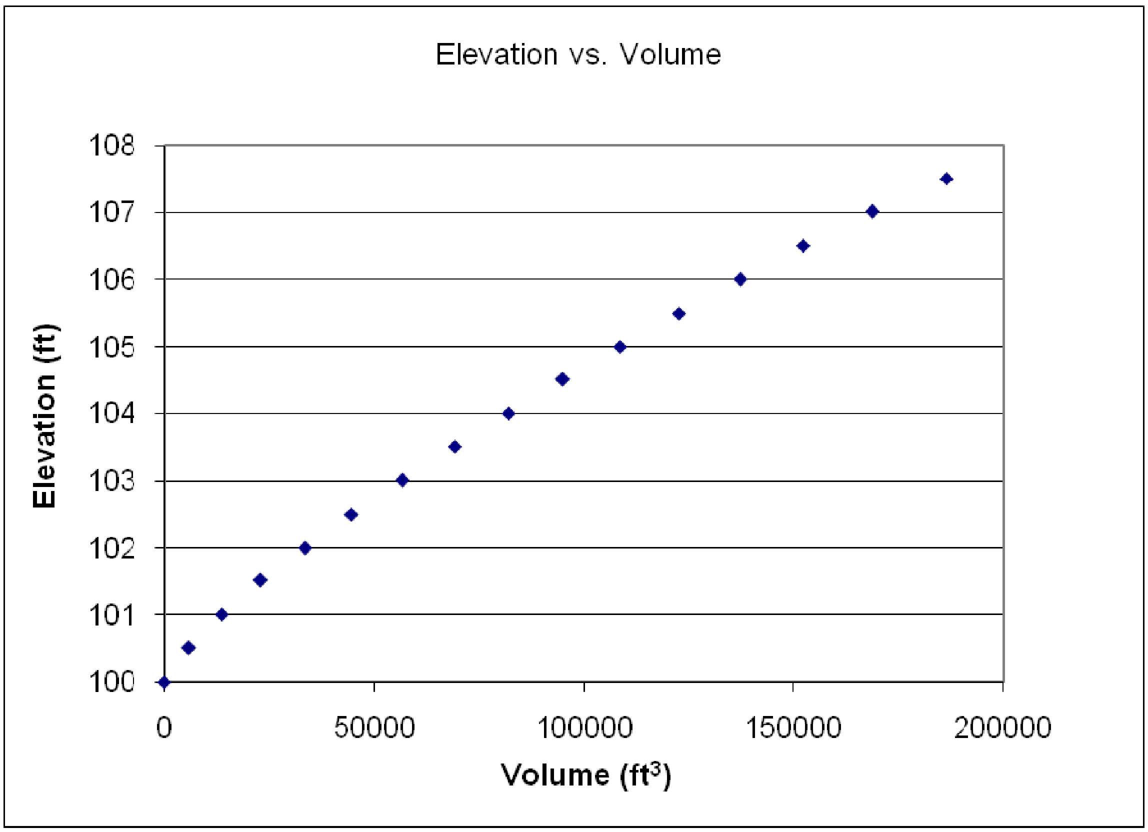

Figure B.4. Plot of elevation versus volume for ARS tests 1 and 2.

Table B.4. Inflow hydrograph for ARS test 1.

Elapsed Time (min)	Discharge (cfs)	Elapsed Time (min)	Discharge (cfs)	Elapsed Time (min)	Discharge (cfs)	Elapsed Time (min)	Discharge (cfs)
0	0.0	26	26.3	52	33.7	78	32.9
1	2.3	27	26.7	53	33.9	79	32.8
2	4.6	28	27.0	54	34.0	80	32.6
3	6.7	29	27.3	55	34.1	81	32.5
4	8.2	30	27.7	56	34.2	82	32.3
5	10.1	31	28.1	57	34.4	83	32.3
6	11.2	32	28.4	58	34.5	84	32.1
7	12.1	33	29.1	59	34.6	85	32.0
8	13.3	34	29.5	60	34.8	86	31.9
9	14.5	35	29.9	61	34.9	87	31.7
10	15.4	36	30.2	62	34.9	88	31.5
11	16.2	37	30.4	63	34.8	89	31.5
12	17.1	38	30.7	64	34.7	90	31.4
13	18.2	39	31.0	65	34.6	91	31.3
14	18.8	40	31.3	66	34.4	92	31.1
15	19.7	41	31.5	67	34.4	93	31.0
16	20.4	42	31.8	68	34.2	94	30.9
17	21.0	43	32.0	69	34.2	95	30.9
18	21.5	44	32.2	70	34.0	96	30.8
19	22.1	45	32.3	71	34.0	97	30.7
20	23.2	46	32.7	72	33.8	98	30.6
21	23.8	47	32.9	73	33.7	99	30.5
22	24.2	48	33.1	74	33.5	100	30.5
23	24.7	49	33.3	75	33.5	101	0.0
24	25.2	50	33.5	76	33.3		
25	25.8	51	33.5	77	33.1		

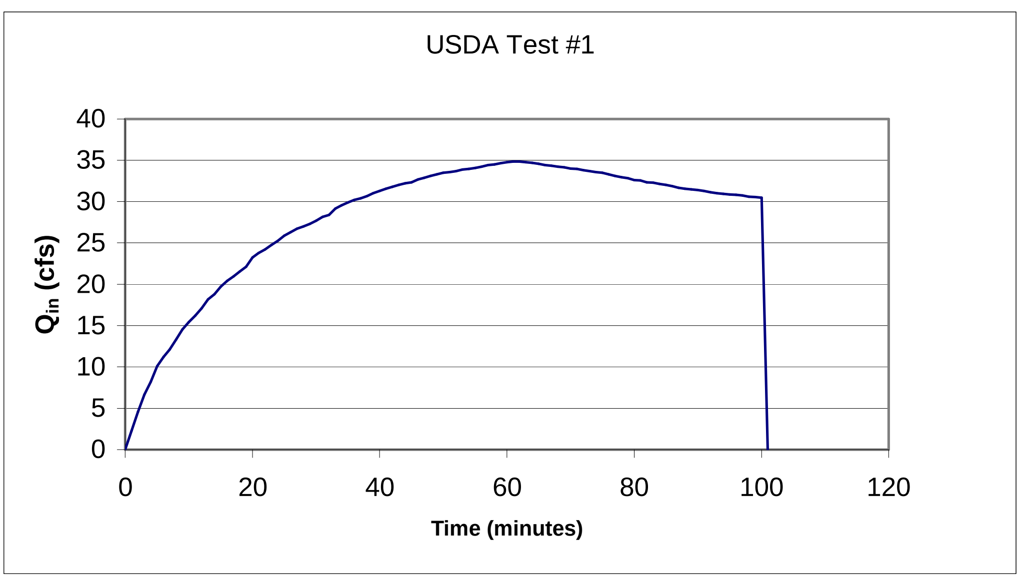

Figure B.5. Plot of ARS test 1 inflow hydrograph.

Table B.5. Summary of key water surface elevations.

First Filling of Reservoir	6/11/1999	
Reservoir Elevation at first filling	103.69 ft	
Test Initiation		
Initiation of Inflow	9:56 AM	6/23/1999
Time of flow over crest	10:48 AM	6/23/1999
Shutdown of Inflow	11:40 AM	6/23/1999
Elevation at Inflow initiation	103.12 ft	

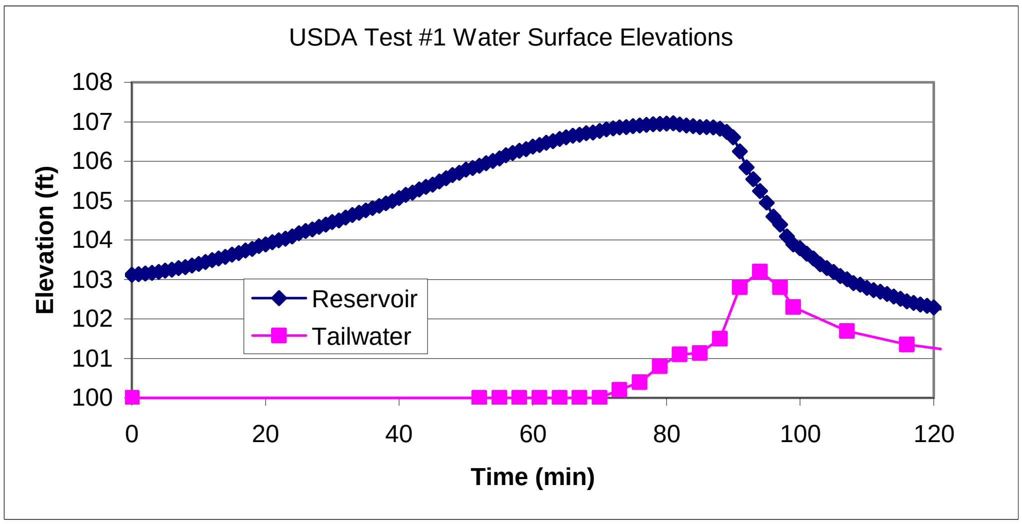

Figure B.6. Plot of water surface elevations upstream (reservoir) and downstream of ARS test 1 embankment.

Discharge Hydrographs

A plot of discharge hydrograph can be found in Figure 1.7, page 7.

Table B.6. NWSB input file for ARS test 1.

```
ARS OVERTOPPING NO. 1
     103.1     105.8     100.0       0.0     105.8       0.0       0.0       0.0
       1.0      10.1      21.3      29.5      32.9      34.9      30.5       0.0
       0.0       0.1       0.3       0.6       0.8       1.0       1.7       1.8
      0.74      0.68      0.65      0.61      0.56       0.5       0.4       0.0
     107.5     106.0     105.0     104.0     103.0     102.0     101.0     100.0
     100.0     101.0     102.0     103.0     104.0       0.0       0.0       0.0
      40.0      50.0      55.0      60.0     200.0       0.0       0.0       0.0
      0.03      0.03      0.03      0.03      0.03       0.0       0.0       0.0
       3.0       3.0       0.0       0.0       0.0       0.0       0.0
       0.0       0.0       0.0       0.0       0.0       0.0       0.0
      0.14       0.3     107.0       0.0       0.0     212.0       5.0
       2.0      15.0      11.0      11.0       0.0       0.0      11.0       0.0
      0.01     0.001       0.1       6.0       0.0       1.0       0.0
       0.0     -0.87     -2.46     -4.53     -6.97     -9.74    -12.81    -16.14
       0.0      0.15       0.3      0.45       0.6      0.75       0.9      1.05
```

Table B.7. NWSB output file for ARS test 1.

```
 ARS OVERTOPPING NO. 1

HI=    103.10  HU=    105.80  HL=    100.00  HPI=       .00  HSP=   105.80  PI=    .0  CA= .000  CB= .00

        (QIN(I),I=1,8)
    1.00     10.10     21.30     29.50     32.90     34.90     30.50       .00

        (TIN(I),I=1,8)
     .00       .10       .30       .60       .80      1.00      1.70      1.80

        (RSA(I),I=1,8)
     .74       .68       .65       .61       .56       .50       .40       .00

        (HSA(I),I=1,8)
  107.50    106.00    105.00    104.00    103.00    102.00    101.00    100.00

        (HSTW(I),I=1,8)
  100.00    101.00    102.00    103.00    104.00       .00       .00       .00

        (BSTW(I),I=1,8)
   40.00     50.00     55.00     60.00    200.00       .00       .00       .00

        (CMTW(I),I=1,8)
     .03       .03       .03       .03       .03       .00       .00       .00

ZU=  3.00  ZD=  3.00  ZC=   .00  GL=   .00  GS=   .00  VMP=   .00  SEDCON=   .00

D50C=   .00  PORC=   .00  UWC=   .00  CNC= .0000  AFRC=   .00  COHC=    .0  UNFCC=   .00

D50S=   .14  PORS=   .30  UWS=107.00  CNS= .0000  AFRS=   .00  COHS= 212.0  UNFCS=  5.00

BR=  2.00  WC=  15.0  CRL=   11.0  SM= 11.00  D50DF=   .00  UNFCDF=   .00   BMX=   11.   BTMX=   11.

DTH=  .010  DBG=  .001   H=   .1000   TEH=    1.8  ERR=   .50  FPT=   1.0  TPR=    .0

        (SPQ(I),I=1,8)
     .00      -.87     -2.46     -4.53     -6.97     -9.74    -12.81    -16.14

        (SPH(I),I=1,8)
     .00       .15       .30       .45       .60       .75       .90      1.05

        AFRA=    .0   TH1= 45.50   H1=  8.06   TH2= 23.25   H2= 19.71   TH3= 12.13   H3= 42.01   SEDCON=   .50

1
```

I	T	DTH	KG	KC	QTOT	QTS	QB	SUB	BT	HY	HC	BO	PPP	HP	TWD	DH	DHH	KIT	AGL
1	.010	.0100	-1	0	0.	0.	0.	1.000	.2	103.1	105.8	.0	.0	.0	.00	.01	.00	0	.0
2	.060	.0500	-1	0	0.	0.	0.	1.000	.2	103.1	105.8	.0	.0	.0	100.25	.01	.00	0	.0
3	.110	.0500	-1	0	0.	0.	0.	1.000	.2	103.2	105.8	.0	.0	.0	100.25	.01	.00	0	.0
4	.160	.0500	-1	0	0.	0.	0.	1.000	.2	103.2	105.8	.0	.0	.0	100.25	.01	.00	0	.0
5	.210	.0500	-1	0	0.	0.	0.	1.000	.2	103.3	105.8	.0	.0	.0	100.25	.01	.00	0	.0
6	.260	.0500	-1	0	0.	0.	0.	1.000	.2	103.5	105.8	.0	.0	.0	100.25	.01	.00	0	.0
7	.310	.0500	-1	0	0.	0.	0.	1.000	.2	103.6	105.8	.0	.0	.0	100.25	.01	.00	0	.0
8	.360	.0500	-1	0	0.	0.	0.	1.000	.2	103.7	105.8	.0	.0	.0	100.25	.01	.00	0	.0
9	.410	.0500	-1	0	0.	0.	0.	1.000	.2	103.9	105.8	.0	.0	.0	100.25	.01	.00	0	.0
10	.460	.0500	-1	0	0.	0.	0.	1.000	.2	104.1	105.8	.0	.0	.0	100.25	.01	.00	0	.0
11	.510	.0500	-1	0	0.	0.	0.	1.000	.2	104.2	105.8	.0	.0	.0	100.25	.01	.00	0	.0
12	.560	.0500	-1	0	0.	0.	0.	1.000	.2	104.4	105.8	.0	.0	.0	100.25	.01	.00	0	.0
13	.610	.0500	-1	0	0.	0.	0.	1.000	.2	104.6	105.8	.0	.0	.0	100.25	.01	.00	0	.0
14	.660	.0500	-1	0	0.	0.	0.	1.000	.2	104.8	105.8	.0	.0	.0	100.25	.01	.00	0	.0
15	.710	.0500	-1	0	0.	0.	0.	1.000	.2	105.0	105.8	.0	.0	.0	100.25	.01	.00	0	.0
16	.760	.0500	-1	0	0.	0.	0.	1.000	.2	105.2	105.8	.0	.0	.0	100.25	.01	.00	0	.0
17	.810	.0500	-1	0	0.	0.	0.	1.000	.2	105.4	105.8	.0	.0	.0	100.25	.01	.00	0	.0
18	.860	.0500	-1	0	0.	0.	0.	1.000	.2	105.6	105.8	.0	.0	.0	100.25	.01	.00	0	.0
19	.870	.0100	-1	0	0.	0.	0.	1.000	.2	105.7	105.8	.0	.0	.0	100.25	.01	.00	0	.0
20	.880	.0100	-1	0	0.	0.	0.	1.000	.2	105.8	105.8	.0	.0	.0	100.25	.01	.00	0	.0
21	.890	.0100	-1	0	0.	0.	0.	1.000	.2	105.8	105.8	.0	.0	.0	100.25	.01	.00	0	.0
22	.900	.0100	-1	0	0.	0.	0.	1.000	.2	105.8	105.8	.0	.0	.0	100.25	.01	.00	0	.0
23	.910	.0100	1	0	0.	0.	0.	1.000	.3	105.9	105.8	.3	.1	.5	100.25	.05	.05	2	.0
24	.921	.0110	1	0	1.	1.	0.	1.000	.5	105.9	105.8	.5	.3	.8	100.25	.10	.10	2	.0
25	.933	.0121	1	0	1.	1.	0.	1.000	.9	106.0	105.8	.9	.4	1.4	100.25	.19	.19	2	.0
26	.946	.0133	1	0	2.	2.	0.	1.000	1.5	106.0	105.8	1.5	.8	2.4	100.25	.32	.32	2	.0
27	.961	.0146	1	0	3.	3.	1.	1.000	2.5	106.1	105.8	2.5	1.3	4.0	100.25	.49	.49	1	.0
28	.977	.0161	1	0	5.	5.	2.	1.000	4.0	106.1	105.8	4.0	2.0	6.3	100.25	.73	.73	1	.0
29	.993	.0161	1	0	6.	6.	4.	1.000	5.8	106.2	105.8	5.8	2.9	9.2	100.25	.93	.94	1	.0
30	1.009	.0161	1	0	7.	7.	7.	1.000	8.1	106.2	105.8	8.1	4.1	12.8	100.25	1.15	1.15	1	.0
31	1.025	.0161	1	0	9.	9.	11.	1.000	10.8	106.3	105.8	10.8	5.4	17.1	100.25	1.36	1.36	1	.0
32	1.026	.0010	2	0	21.	-3.	24.	1.000	10.8	106.3	105.5	10.8	19.2	.3	100.25	.30	.30	5	.0
33	1.028	.0011	2	0	46.	-3.	49.	1.000	10.8	106.3	105.0	10.8	20.7	.8	100.25	.52	.52	4	.0
34	1.029	.0011	2	0	89.	-3.	91.	1.000	10.8	106.3	104.3	10.8	22.6	1.5	100.75	.70	.70	4	.0
35	1.030	.0011	2	0	148.	-3.	151.	1.000	10.8	106.3	103.5	10.8	24.9	2.3	100.75	.82	.82	5	.0
36	1.031	.0011	2	0	221.	-3.	224.	1.000	10.8	106.3	102.7	10.8	27.4	3.1	101.25	.87	.88	9	.0
37	1.032	.0011	2	0	303.	-3.	305.	1.000	10.8	106.3	101.8	10.8	29.8	4.0	101.75	.87	.88	19	.0
38	1.033	.0011	2	0	389.	-2.	391.	1.000	10.8	106.2	101.0	10.8	32.2	4.8	101.75	.85	.86	39	.0
39	1.034	.0001	2	0	391.	-2.	393.	1.000	10.8	106.2	100.9	10.8	32.3	4.9	102.25	.04	.04	3	.0
40	1.034	.0001	2	0	395.	-2.	398.	1.000	10.8	106.2	100.9	10.8	32.4	4.9	102.25	.04	.04	1	.0
41	1.034	.0001	2	0	400.	-2.	402.	1.000	10.8	106.2	100.9	10.8	32.6	4.9	102.25	.04	.04	1	.0
42	1.034	.0001	2	0	404.	-2.	407.	1.000	10.8	106.2	100.8	10.8	32.7	5.0	102.25	.04	.04	1	.0
43	1.034	.0001	2	0	409.	-2.	411.	1.000	10.8	106.2	100.8	10.8	32.8	5.0	102.25	.04	.04	1	.0
44	1.035	.0001	2	0	413.	-2.	416.	1.000	10.8	106.2	100.7	10.8	32.9	5.1	102.25	.04	.04	1	.0
45	1.035	.0001	2	0	418.	-2.	420.	1.000	10.8	106.2	100.7	10.8	33.1	5.1	102.25	.04	.04	0	.0
46	1.035	.0001	2	0	422.	-2.	424.	1.000	10.8	106.2	100.6	10.8	33.2	5.2	102.25	.04	.04	0	.0

47	1.035	.0001	2	0	427.	-2.	429.	1.000	10.8	106.2	100.6	10.8	33.3	5.2	102.25	.04	.04	1	.0
48	1.035	.0001	2	0	431.	-2.	433.	1.000	10.8	106.2	100.6	10.8	33.4	5.2	102.25	.04	.04	1	.0
49	1.035	.0001	2	0	435.	-2.	437.	1.000	10.8	106.2	100.5	10.8	33.5	5.3	102.25	.04	.04	1	.0
50	1.035	.0002	2	0	439.	-2.	441.	1.000	10.8	106.2	100.5	10.8	33.7	5.3	102.25	.04	.04	1	.0

I	T	DTH	KG	KC	QTOT	QTS	QB	SUB	BT	HY	HC	BO	PPP	HP	TWD	DH	DHH	KIT	AGL
51	1.035	.0002	2	0	442.	-2.	444.	1.000	10.8	106.2	100.4	10.8	33.8	5.4	102.25	.04	.04	2	.0
52	1.036	.0002	2	0	446.	-2.	447.	1.000	10.8	106.1	100.4	10.8	33.9	5.4	102.25	.04	.04	2	.0
53	1.036	.0002	2	0	449.	-2.	450.	1.000	10.8	106.1	100.4	10.8	34.0	5.4	102.25	.04	.04	2	.0
54	1.036	.0002	2	0	451.	-2.	453.	1.000	10.8	106.1	100.3	10.8	34.1	5.5	102.25	.03	.03	2	.0
55	1.036	.0003	2	0	454.	-2.	455.	1.000	10.8	106.1	100.3	10.8	34.2	5.5	102.25	.03	.03	2	.0
56	1.037	.0003	2	0	456.	-2.	457.	1.000	10.8	106.1	100.3	10.8	34.2	5.5	102.25	.03	.03	2	.0
57	1.037	.0003	2	0	457.	-2.	459.	1.000	10.8	106.1	100.2	10.8	34.3	5.6	102.25	.03	.03	2	.0
58	1.037	.0003	2	0	458.	-2.	460.	1.000	10.8	106.1	100.2	10.8	34.4	5.6	102.25	.03	.03	2	.0
59	1.038	.0004	2	0	459.	-1.	461.	1.000	10.8	106.1	100.2	10.8	34.5	5.6	102.25	.02	.02	2	.0
60	1.038	.0004	2	0	459.	-1.	461.	1.000	10.8	106.0	100.2	10.8	34.5	5.6	102.25	.02	.02	2	.0
61	1.038	.0004	2	0	459.	-1.	460.	1.000	10.8	106.0	100.2	10.8	34.6	5.6	102.25	.02	.02	2	.0
62	1.039	.0005	2	0	459.	-1.	460.	1.000	10.8	106.0	100.1	10.8	34.6	5.7	102.25	.02	.02	2	.0
63	1.040	.0005	2	0	458.	-1.	459.	1.000	10.8	106.0	100.1	10.8	34.7	5.7	102.25	.02	.02	3	.0
64	1.040	.0006	2	0	456.	-1.	457.	1.000	10.8	105.9	100.1	10.8	34.7	5.7	102.25	.01	.01	3	.0
65	1.041	.0007	2	0	454.	-1.	455.	1.000	10.8	105.9	100.1	10.8	34.8	5.7	102.25	.01	.01	3	.0
66	1.041	.0007	2	0	451.	0.	452.	1.000	10.8	105.9	100.1	10.8	34.8	5.7	102.25	.01	.01	3	.0
67	1.042	.0008	2	0	448.	0.	449.	1.000	10.8	105.8	100.1	10.8	34.8	5.7	102.25	.01	.01	3	.0
68	1.043	.0009	2	0	445.	0.	445.	1.000	10.8	105.8	100.1	10.8	34.8	5.7	102.25	.01	.01	3	.0
69	1.044	.0010	2	0	440.	0.	440.	1.000	10.8	105.7	100.1	10.8	34.9	5.7	102.25	.01	.01	3	.0
70	1.045	.0011	2	0	435.	0.	435.	1.000	10.8	105.7	100.0	10.8	34.9	5.8	102.25	.01	.01	3	.0
71	1.046	.0012	2	0	430.	0.	430.	1.000	10.8	105.6	100.0	10.8	34.9	5.8	102.25	.01	.01	3	.0
72	1.048	.0013	2	0	424.	0.	424.	1.000	10.8	105.6	100.0	10.8	34.9	5.8	102.25	.01	.01	3	.0
73	1.049	.0014	2	0	417.	0.	417.	1.000	10.8	105.5	100.0	10.8	34.9	5.8	102.25	.01	.01	3	.0
74	1.051	.0015	2	0	409.	0.	409.	1.000	10.8	105.4	100.0	10.8	35.0	5.8	102.25	.00	.00	3	.0
75	1.052	.0017	2	0	401.	0.	401.	1.000	10.8	105.4	100.0	10.8	35.0	5.8	102.25	.00	.00	3	.0
76	1.054	.0019	2	0	393.	0.	393.	1.000	10.8	105.3	100.0	10.8	35.0	5.8	102.25	.00	.00	3	.0
77	1.056	.0021	2	0	383.	0.	383.	1.000	10.8	105.2	100.0	10.8	35.0	5.8	102.25	.00	.00	3	.0
78	1.058	.0023	2	0	373.	0.	373.	1.000	10.8	105.1	100.0	10.8	35.0	5.8	102.25	.00	.00	3	.0
79	1.061	.0025	2	0	362.	0.	362.	1.000	10.8	105.0	100.0	10.8	35.0	5.8	102.25	.00	.00	3	.0
80	1.064	.0027	2	0	350.	0.	350.	1.000	10.8	104.9	100.0	10.8	35.0	5.8	102.25	.00	.00	3	.0
81	1.067	.0030	2	0	338.	0.	338.	1.000	10.8	104.8	100.0	10.8	35.0	5.8	102.25	.00	.00	3	.0
82	1.070	.0033	2	0	325.	0.	325.	1.000	10.8	104.6	100.0	10.8	35.0	5.8	102.25	.00	.00	3	.0
83	1.074	.0036	2	0	312.	0.	312.	1.000	10.8	104.5	100.0	10.8	35.0	5.8	102.25	.00	.00	3	.0
84	1.078	.0040	2	0	297.	0.	297.	1.000	10.8	104.4	100.0	10.8	35.0	5.8	101.75	.00	.00	1	.0
85	1.082	.0044	3	0	282.	0.	282.	1.000	10.8	104.2	100.0	10.8	.0	2.2	101.75	.00	.00	2	.0
86	1.087	.0049	3	0	267.	0.	267.	1.000	10.8	104.1	100.0	10.8	.0	2.1	101.75	.00	.00	2	.0
87	1.092	.0053	3	0	252.	0.	252.	1.000	10.8	103.9	100.0	10.8	.0	2.0	101.75	.00	.00	2	.0
88	1.098	.0059	3	0	234.	0.	234.	1.000	10.8	103.7	100.0	10.8	.0	2.0	101.75	.00	.00	0	.0
89	1.105	.0065	3	0	216.	0.	216.	1.000	10.8	103.5	100.0	10.8	.0	1.8	101.75	.00	.00	2	.0
90	1.112	.0071	3	0	200.	0.	200.	1.000	10.8	103.4	100.0	10.8	.0	1.8	101.75	.00	.00	2	.0
91	1.120	.0078	3	0	185.	0.	185.	1.000	10.8	103.2	100.0	10.8	.0	1.7	101.75	.00	.00	2	.0
92	1.128	.0086	3	0	169.	0.	169.	1.000	10.8	103.0	100.0	10.8	.0	1.6	101.25	.00	.00	2	.0

93	1.138	.0095	3	0	154.	0.	154.	1.000	10.8	102.8	100.0	10.8	.0	1.5	101.25	.00	.00	2	.0
94	1.148	.0104	3	0	139.	0.	139.	1.000	10.8	102.6	100.0	10.8	.0	1.4	101.25	.00	.00	2	.0
95	1.159	.0114	3	0	126.	0.	126.	1.000	10.8	102.5	100.0	10.8	.0	1.3	101.25	.00	.00	2	.0
96	1.172	.0126	3	0	112.	0.	112.	1.000	10.8	102.3	100.0	10.8	.0	1.2	101.25	.00	.00	2	.0
97	1.186	.0138	3	0	100.	0.	100.	1.000	10.8	102.1	100.0	10.8	.0	1.2	101.25	.00	.00	2	.0
98	1.201	.0152	3	0	89.	0.	89.	1.000	10.8	102.0	100.0	10.8	.0	1.1	101.25	.00	.00	2	.0
99	1.218	.0167	3	0	79.	0.	79.	1.000	10.8	101.8	100.0	10.8	.0	1.0	100.75	.00	.00	2	.0
100	1.236	.0184	3	0	70.	0.	70.	1.000	10.8	101.7	100.0	10.8	.0	.9	100.75	.00	.00	2	.0
I	T	DTH	KG	KC	QTOT	QTS	QB	SUB	BT	HY	HC	BO	PPP	HP	TWD	DH	DHH	KIT	AGL
101	1.256	.0203	3	0	62.	0.	62.	1.000	10.8	101.5	100.0	10.8	.0	.9	100.75	.00	.00	2	.0
102	1.279	.0223	3	0	55.	0.	55.	1.000	10.8	101.4	100.0	10.8	.0	.8	100.75	.00	.00	2	.0
103	1.303	.0245	3	0	50.	0.	50.	1.000	10.8	101.3	100.0	10.8	.0	.8	100.75	.00	.00	2	.0
104	1.330	.0270	3	0	45.	0.	45.	1.000	10.8	101.2	100.0	10.8	.0	.7	100.75	.00	.00	2	.0

KTT= 0 I= 104 T= 1.33

OUTPUT SUMMARY

QBP	MAX OUTFLOW(CFS) THRU BREACH	461.
TP	TIME(HR) AT WHICH PEAK OUTFLOW OCCURS	1.04
QP	MAX TOTAL OUTFLOW(CFS) OCCURRING AT TIME TP	459.
TRS	DURATION(HR) OF RISING LIMB OF HYDROGRAPH	.03
TB	TIME(HR) AT WHICH SIGN. RISE IN OUTFLOW STARTS	1.01
BRD	FINAL DEPTH(FT) OF BREACH	5.80
BRW	TOP WIDTH(FT) OF BREACH AT PEAK BREACH FLOW	10.84
HU	ELEV(FT) OF TOP OF DAM	105.80
HY	FINAL ELEV(FT) OF RESERVOIR WATER SURFACE	101.24
HC	FINAL ELEV(FT) OF BOTTOM OF BREACH	100.000
AGL	ACUTE ANGLE THAT BREACH SIDE MAKES WITH VERTICAL AT QBP	.000
QO	OUTFLOW (CFS) AT T=0.0	.0000
Z	SIDE SLOPE OF BREACH (FT/FT) AT PEAK BREACH FLOW	.00
TFH	TIME OF FAILURE (HR) WHICH IS LINEAR EQUIVALENT OF TRS OBTAINED BY USING SIMPLIFIED DAM-BREAK DISCHARGE EQUATION	.02
TFHI	TIME OF FAILURE (HR) WHICH IS LINEAR EQUIVALENT OF TRS OBTAINED BY INTEGRATING QB VS TIME FROM T=0 TO T=TP	.01
BO	BOTTOM WIDTH (FT) OF BREACH AT PEAK BREACH FLOW	10.84

1

```
0TIME   .0    50.0     100.0     150.0     200.0     250.0     300.0     350.0     400.0     450.0     500.0     DISCHARGE
    .880*         .         .         .         .         .         .         .         .         .         .          0.
    .890*         .         .         .         .         .         .         .         .         .         .          0.
    .900*         .         .         .         .         .         .         .         .         .         .          0.
    .910*         .         .         .         .         .         .         .         .         .         .          0.
    .920*         .         .         .         .         .         .         .         .         .         .          1.
    .930*         .         .         .         .         .         .         .         .         .         .          1.
    .940*         .         .         .         .         .         .         .         .         .         .          2.
    .950*         .         .         .         .         .         .         .         .         .         .          2.
    .960.*        .         .         .         .         .         .         .         .         .         .          3.
    .970.*        .         .         .         .         .         .         .         .         .         .          4.
    .980.*        .         .         .         .         .         .         .         .         .         .          5.
    .990.*        .         .         .         .         .         .         .         .         .         .          6.
   1.000.*        .         .         .         .         .         .         .         .         .         .          7.
   1.010. *       .         .         .         .         .         .         .         .         .         .          8.
   1.020. *       .         .         .         .         .         .         .         .         .         .          8.
   1.030.         .         .         .  *      .         .         .         .         .         .         .        163.
   1.040.         .         .         .         .         .         .         .         .         .*        .        456.
   1.050.         .         .         .         .         .         .         .         . *       .         .        412.
   1.060.         .         .         .         .         .         .         .  *      .         .         .        366.
   1.070.         .         .         .         .         .         .    *    .         .         .         .        325.
   1.080.         .         .         .         .         .       * .         .         .         .         .        289.
   1.090.         .         .         .         .         . *       .         .         .         .         .        258.
   1.100.         .         .         .         .     *   .         .         .         .         .         .        229.
   1.110.         .         .         .         .*        .         .         .         .         .         .        204.
   1.120.         .         .         .      *  .         .         .         .         .         .         .        184.
   1.130.         .         .         .  *      .         .         .         .         .         .         .        166.
   1.140.         .         .         *         .         .         .         .         .         .         .        151.
   1.150.         .         .      *  .         .         .         .         .         .         .         .        137.
   1.160.         .         .    *    .         .         .         .         .         .         .         .        125.
   1.170.         .         .  *      .         .         .         .         .         .         .         .        115.
   1.180.         .         .*        .         .         .         .         .         .         .         .        105.
   1.190.         .        *.         .         .         .         .         .         .         .         .         97.
   1.200.         .       * .         .         .         .         .         .         .         .         .         90.
   1.210.         .      *  .         .         .         .         .         .         .         .         .         84.
   1.220.         .     *   .         .         .         .         .         .         .         .         .         78.
   1.230.         .    *    .         .         .         .         .         .         .         .         .         73.
   1.240.         .   *     .         .         .         .         .         .         .         .         .         69.
   1.250.         .  *      .         .         .         .         .         .         .         .         .         65.
   1.260.         . *       .         .         .         .         .         .         .         .         .         61.
```

Table B.8. SIMBA input file for ARS test 1.

```
BREACH    01/01/2005
WHA
WDC
OPTIONS   00101
IHW
IHH
USL       3
DSL       3
HDM       5.8
CWD       15
CEL       105.8
BKD       116.6
UDS       212
KDI       5.77
CSS       0
DWD       6
NSS       3
ELE       103.12
HCMODEL   6
STRUCTURE C
          100       0
          100.5     5837
          101       13591
          101.5     22869
          102       33323
          102.5     44649
          103       56628
          103.5     69086
          104       81893
          104.5     95048
          105       108552
          105.5     122491
          106       136953
          106.5     152198
          107       168490
          107.5     186088
ENDTABLE
HYD
          .0020833333
          0         0.00
          0.0167    2.29
          0.0333    4.57
          0.0500    6.66
          0.0667    8.20
          0.0833    10.08
          0.1000    11.19
          0.1167    12.11
          0.1333    13.30
          0.1500    14.52
          0.1667    15.43
          0.1833    16.20
          0.2000    17.09
          0.2167    18.17
          0.2333    18.77
          0.2500    19.71
          0.2667    20.39
          0.2833    20.96
          0.3000    21.53
          0.3167    22.11
          0.3333    23.23
          0.3500    23.77
          0.3667    24.19
          0.3833    24.74
          0.4000    25.23
          0.4167    25.85
          0.4333    26.28
          0.4500    26.72
          0.4667    26.97
          0.4833    27.29
          0.5000    27.67
          0.5167    28.12
          0.5333    28.37
          0.5500    29.15
          0.5667    29.54
          0.5833    29.86
          0.6000    30.19
          0.6167    30.39
          0.6333    30.65
          0.6500    30.98
          0.6667    31.25
          0.6833    31.52
          0.7000    31.79
          0.7167    31.99
          0.7333    32.19
          0.7500    32.32
          0.7667    32.66
          0.7833    32.86
          0.8000    33.07
          0.8167    33.27
          0.8333    33.48
          0.8500    33.55
          0.8667    33.68
          0.8833    33.89
          0.9000    33.96
          0.9167    34.10
          0.9333    34.23
          0.9500    34.44
          0.9667    34.51
          0.9833    34.65
          1.0000    34.79
          1.0167    34.86
          1.0333    34.86
          1.0500    34.79
          1.0667    34.72
          1.0833    34.58
          1.1000    34.44
          1.1167    34.37
          1.1333    34.23
          1.1500    34.16
          1.1667    34.03
          1.1833    33.96
          1.2000    33.82
          1.2167    33.68
          1.2333    33.55
          1.2500    33.48
          1.2667    33.27
          1.2833    33.07
          1.3000    32.93
          1.3167    32.80
          1.3333    32.59
          1.3500    32.53
          1.3667    32.32
          1.3833    32.26
          1.4000    32.12
          1.4167    31.99
          1.4333    31.85
          1.4500    31.65
          1.4667    31.52
          1.4833    31.45
          1.5000    31.38
          1.5167    31.25
          1.5333    31.12
          1.5500    30.98
          1.5667    30.92
          1.5833    30.85
          1.6000    30.79
          1.6167    30.72
          1.6333    30.59
          1.6500    30.52
          1.6667    30.46
          1.6833    0.00
ENDTABLE
```

Table B.9. SIMBA output file for ARS test 1, reduced.

Time	Qin	Qout	Qb	Qd	El	HC Pos	Attack	Hh	Width	Hc
0	0	0	0	0	103.12	32.4	0	0	0	105.8
0.1	11.1	0	0	0	103.203	32.4	0	0	0	105.8
0.2	17	0	0	0	103.405	32.4	0	0	0	105.8
0.3	21.5	0	0	0	103.677	32.4	0	0	0	105.8
0.4	25.2	0	0	0	104.004	32.4	0	0	0	105.8
0.5	27.6	0	0	0	104.364	32.4	0	0	0	105.8
0.6	30.1	0	0	0	104.75	32.4	0	0	0	105.8
0.7	31.8	0	0	0	105.155	32.4	0	0	0	105.8
0.8	33	0	0	0	105.567	32.4	0	0	0	105.8
0.9	34	1	0	1.4	105.978	32.4	0.03	0.101	0.155	105.8
1	34.8	8	0	8	106.328	32.277	1.24	1.019	0.308	105.8
1.033	34.9	11	1	10.5	106.426	32.217	2.34	1.497	0.368	105.8
1.067	34.7	14	1	12.9	106.512	32.139	3.86	2.045	0.446	105.8
1.1	34.5	16	1	15	106.583	32.031	5.76	2.651	0.554	105.8
1.133	34.2	18	2	16.7	106.645	31.862	8.04	3.307	0.722	105.8
1.167	34	21	3	17.7	106.699	31.507	10.65	4.006	1.078	105.8
1.2	33.8	22	7	15.2	106.743	30.07	13.55	4.741	2.514	105.8
1.233	33.6	24	13	11	106.781	28.296	16.67	5.505	4.289	105.8
1.267	33.3	25	19	6	106.813	26.464	18.26	5.8	6.121	105.8
1.3	32.9	26	26	0.3	106.839	24.584	18.96	5.8	8.001	105.8
1.333	32.6	27	27	0	106.859	22.666	19.53	5.8	8.116	105.8
1.367	32.3	28	28	0	106.876	20.717	19.99	5.8	8.15	105.8
1.4	32.1	29	29	0	106.889	18.743	20.36	5.8	8.177	105.8
1.433	31.9	42	42	0	106.892	16.704	26.2	5.616	8.987	105.568
1.467	31.5	117	117	0	106.736	13.744	44.73	4.656	11.947	104.581
1.5	31.4	221	221	0	106.178	10.205	48.6	3.446	15.485	103.402
1.533	31.1	206	206	0	105.41	8.743	35.48	2.937	16.947	102.914
1.567	30.9	168	168	0	104.73	7.884	24.73	2.642	17.806	102.628
1.6	30.8	132	132	0	104.197	7.32	17.54	2.45	18.371	102.44
1.633	30.6	105	105	0	103.794	6.927	12.9	2.316	18.763	102.309
1.667	30.5	85	85	0	103.493	6.639	9.9	2.218	19.051	102.213
1.7	0	63	63	0	103.179	6.425	6.99	2.146	19.265	102.142
1.733	0	45	45	0	102.918	6.272	4.86	2.094	19.418	102.091
1.767	0	34	34	0	102.723	6.141	3.51	2.049	19.55	102.047
1.8	0	26	26	0	102.575	6.025	2.64	2.01	19.666	102.008
1.833	0	20	20	0	102.456	5.921	2.04	1.976	19.77	101.974
1.867	0	17	17	0	102.359	5.827	1.62	1.944	19.863	101.942
1.9	0	14	14	0	102.28	5.742	1.31	1.916	19.948	101.914
1.933	0	12	12	0	102.214	5.663	1.09	1.889	20.027	101.888
1.967	0	10	10	0	102.158	5.59	0.92	1.865	20.1	101.863
2	0	9	9	0	102.11	5.522	0.79	1.842	20.169	101.841
2.2	0	5	5	0	101.903	5.175	0.4	1.726	20.515	101.725
2.4	0	3	3	0	101.774	4.897	0.27	1.633	20.793	101.632
2.6	0	3	3	0	101.674	4.651	0.21	1.551	21.04	101.55
2.8	0	3	3	0	101.587	4.42	0.18	1.474	21.27	101.473
3	0	2	2	0	101.508	4.199	0.15	1.401	21.491	101.4
3.2	0	2	2	0	101.428	3.989	0.13	1.33	21.701	101.33
3.4	0	2	2	0	101.357	3.789	0.11	1.264	21.901	101.263
3.6	0	2	2	0	101.291	3.592	0.11	1.198	22.099	101.197
3.8	0	2	2	0	101.224	3.395	0.1	1.132	22.295	101.132
4	0	2	2	0	101.158	3.201	0.09	1.068	22.49	101.067
4.2	0	2	2	0	101.093	3.007	0.08	1.003	22.683	101.002
4.4	0	2	2	0	101.028	2.815	0.08	0.939	22.875	100.938
4.6	0	2	2	0	100.957	2.628	0.06	0.877	23.063	100.876
4.8	0	1	1	0	100.893	2.453	0.05	0.818	23.237	100.818
5	0	1	1	0	100.834	2.285	0.05	0.762	23.405	100.762
5.2	0	1	1	0	100.778	2.121	0.04	0.707	23.57	100.707
5.4	0	1	1	0	100.722	1.958	0.04	0.653	23.732	100.653
5.6	0	1	1	0	100.668	1.797	0.03	0.6	23.893	100.599
5.8	0	1	1	0	100.614	1.638	0.03	0.547	24.052	100.546
6	0	1	1	0	100.56	1.479	0.03	0.494	24.211	100.493

SUMMARY:

OTBegins	0.858
HCAdv	0.94
TauSwitch	0.000
Breach St	1.423
HCDown	0.000
BrEnd	0.000

APPENDIX C

ARS TEST 2 EXPERIMENT SUMMARY

AND MODEL FILES

Table C.1. ARS test 2 physical dimensions.

Embankment Dimensions	
Height of embankment	7.3 ft
Elevation of embankment	107.3 ft
Top Length	24 ft
Top Width	6ft
Upstream Slope	3/1 (H/V)
Downstream Slope	3/1 (H/V)
Elevation @ Base	100.0 ft
Embankment Width @ Toe	51 ft
Test Section Dimensions	
Height of Test Section	5.8 ft
Notch Base width	6.0 ft
Notch Side Slopes	3/1 (H/V)
Notch Depth	1.5 ft
Crest width @ Notch	16 ft
Elevation of Crest	105.8 ft

Figure C.1. ARS test 2 in first minutes of flow over crest.

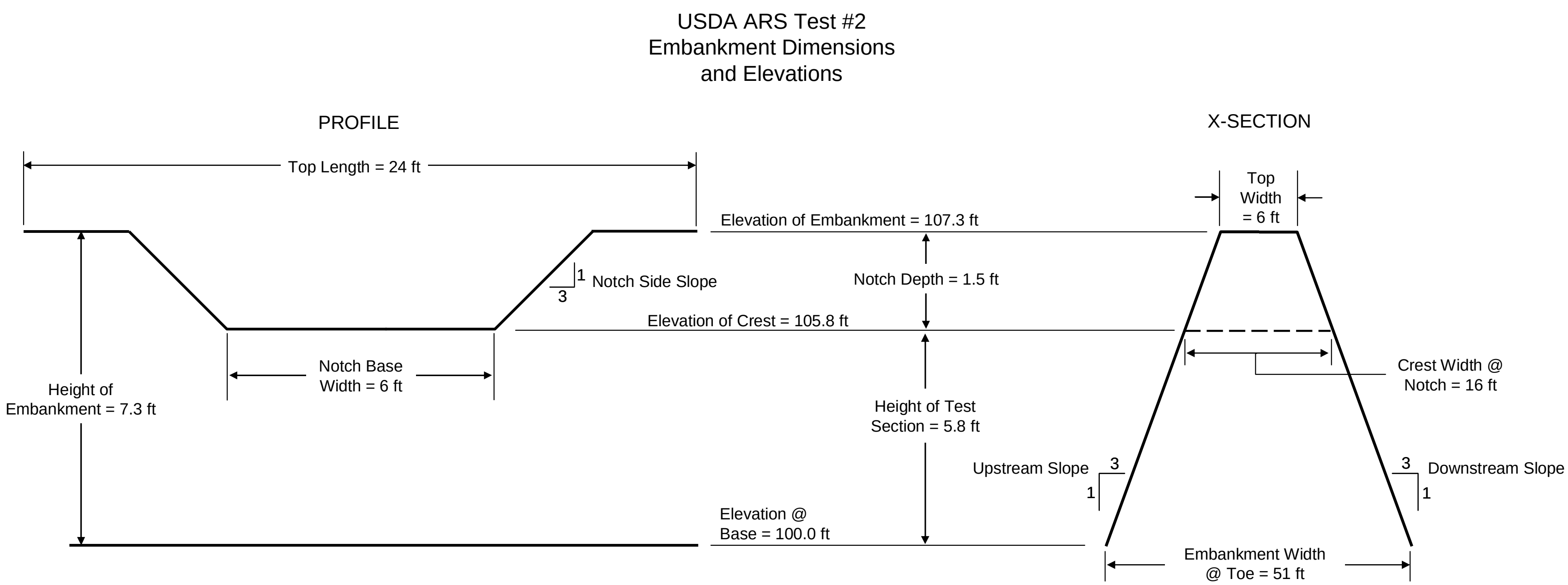

Figure C.2. As-built profile and cross section of ARS test 2 embankment.

Table C.2. Summary of soil analysis for ARS test 2.

Gradation		
% Clay < 0.002 mm	26	
% Silt > 0.002 mm	49	
% Sand > 0.105 mm	25	
Plasticity Index	17	
USCS	CL	
Grain Density g/cm^3	2.67	
Unconfined Compressive Strength q_u (lb/ft^2)	1423	
Average Dry Density (lb/ft^3)	102.96	
Average Water Content @ construction, %	16.4	
Average Total Density (lb/ft^3)	120	
porosity	0.28	
Erodibility Coefficient kd (ft/h)/(lb/ft^2)	0.022	
Critical stress τ_c lb/ft^2	0.3	
Construction		
Compaction Effort	~4000 ft-lb/ft^3	
Loose Lift Thickness	0.5 ft	
Compacted lift thickness	0.4 ft	
Constructed 9/1998		
Seive Analysis	mm	% Finer
0.002 mm	0.002	26
0.005 mm	0.005	32
# 200 (0.075 mm)	0.075	75
# 10 (2.00 mm)	2	100

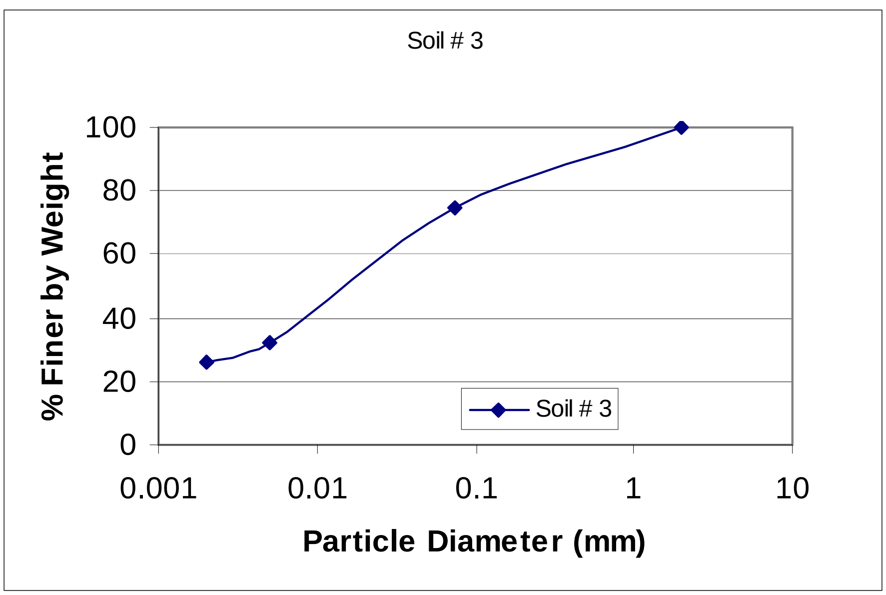

Figure C.3. Plot of particle size distribution for embankment material of ARS test 2.

Table C.3. Inflow hydrograph for ARS test 2.

Elapsed Time (hrs)	Discharge (cfs)	Elapsed Time (hrs)	Discharge (cfs)	Elapsed Time (hrs)	Discharge (cfs)
0.000	0.0	0.820	30.0	1.470	32.5
0.026	2.9	0.836	30.2	1.520	32.5
0.036	7.9	0.853	30.3	1.536	32.6
0.053	11.8	0.870	30.4	1.620	32.6
0.070	14.7	0.886	30.4	1.636	32.7
0.086	15.7	0.903	30.6	1.670	32.7
0.103	16.2	0.920	30.7	1.686	32.8
0.120	16.8	0.936	30.8	1.786	32.8
0.136	17.3	0.953	31.0	1.803	32.9
0.153	18.0	0.970	31.1	1.870	32.9
0.170	18.4	0.986	31.2	1.886	33.0
0.186	19.0	1.003	31.2	2.036	33.0
0.203	19.7	1.020	31.3	2.120	33.1
0.220	20.2	1.036	31.4	5.036	33.1
0.236	20.8	1.053	31.4	6.036	33.4
0.253	21.2	1.070	31.5	7.036	33.6
0.270	21.5	1.086	31.6	8.036	33.5
0.286	21.9	1.103	31.6	9.036	33.6
0.303	22.3	1.120	31.7	10.036	33.6
0.320	22.6	1.136	31.7	11.036	33.5
0.336	23.1	1.153	31.8	12.036	33.6
0.353	23.5	1.186	31.8	13.036	33.8
0.370	23.9	1.203	31.9	14.036	33.8
0.386	24.4	1.220	32.0	15.036	33.6
0.403	24.9	1.236	32.0	16.036	33.5
0.420	25.3	1.253	32.1	17.036	33.5
0.436	25.6	1.286	32.1	18.036	33.6
0.453	25.9	1.303	32.2	19.036	33.7
0.470	26.2	1.336	32.2	20.036	33.7
0.486	26.6	1.353	32.3	20.120	33.6
0.503	26.8	1.370	32.4	20.420	33.6
0.520	27.1	1.453	32.4	20.536	0.0
0.536	27.3				
0.553	27.5				
0.570	27.8				
0.586	27.9				
0.603	28.1				
0.620	28.3				
0.636	28.5				
0.653	28.6				
0.670	28.7				
0.686	29.0				
0.703	29.1				
0.720	29.3				
0.736	29.6				
0.753	29.6				
0.770	29.8				
0.786	29.8				
0.803	29.9				

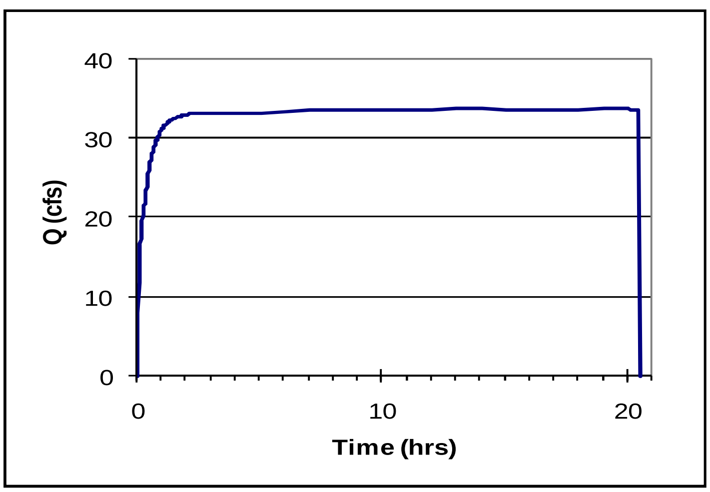

Figure C4. Plot of ARS test 2 inflow hydrograph.

Reservoir Storage

See ARS test 1, Table B.3 and Figure B.4.

Table C.4. Summary of key water surface elevations for ARS test 2.

First Filling of Reservoir	7/16/1999	
Reservoir Elevation at first filling	104.68 ft	
<u>Test Initiation</u>		
Initiation of Inflow	8:58 AM	7/27/1999
Time of flow over crest	9:57 AM	7/27/1999
Shutdown of Inflow	5:30 AM	7/28/1999
Elevation at Inflow initiation	103.07 ft	

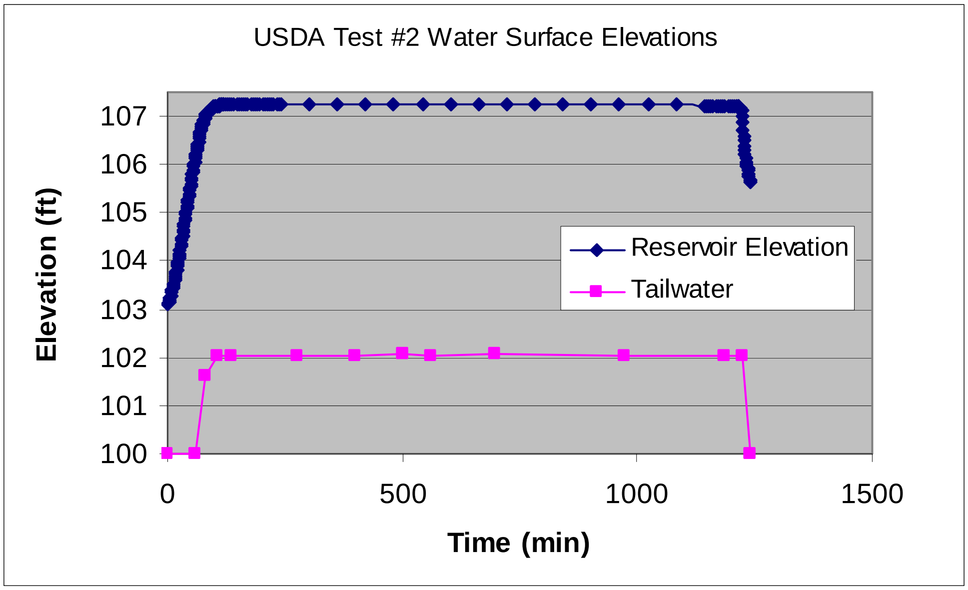

Figure C.5. Plot of water surface elevations upstream (Reservoir Elevation) and downstream (Tailwater) of ARS test 1 embankment.

Discharge Hydrograph

A plot of the discharge hydrograph can be found in Figure 1.8, page 7.

Table C.5. NWSB input file for ARS test 2.

```
ARS OVERTOPPING NO. 2
    103.07     105.8     100.0       0.0     105.8      17.0      0.02      0.84
       1.0     21.85     27.26     31.55      33.1      33.1     33.65     33.65
       0.0      0.29      0.54      1.09      2.12       4.0      12.0      20.4
      0.74      0.68      0.65      0.61      0.56       0.5       0.4       0.0
     107.5     106.0     105.0     104.0     103.0     102.0     101.0     100.0
     100.0     101.0     102.0     103.0     104.0       0.0       0.0       0.0
      40.0      50.0      55.0      60.0     200.0       0.0       0.0       0.0
      0.03      0.03      0.03      0.03      0.03       0.0       0.0       0.0
       3.0       3.0       0.0       0.0       0.0       0.0       0.0
       0.0       0.0       0.0       0.0       0.0       0.0       0.0
     0.014      0.28     120.0       0.0      40.0     712.0     107.0
       2.0      16.0      12.0      11.0       0.0       0.0      12.0       0.0
      0.02     0.001       0.1      20.0       0.0       1.0       0.0
       0.0     -1.05     -2.96     -5.43     -8.37    -11.69    -15.37    -19.37
       0.0      0.15       0.3      0.45       0.6      0.75       0.9      1.05
```

Table C.6. NWSB output file for ARS test 2.

```
ARS OVERTOPPING NO. 2

  HI=    103.07  HU=    105.80  HL=    100.00  HPI=       .00  HSP=   105.80  PI=  17.0  CA= .020  CB= .84

          (QIN(I),I=1,8)
      1.00     21.85     27.26     31.55     33.10     33.10     33.65     33.65

          (TIN(I),I=1,8)
       .00       .29       .54      1.09      2.12      4.00     12.00     20.40

          (RSA(I),I=1,8)
       .74       .68       .65       .61       .56       .50       .40       .00

          (HSA(I),I=1,8)
    107.50    106.00    105.00    104.00    103.00    102.00    101.00    100.00

          (HSTW(I),I=1,8)
    100.00    101.00    102.00    103.00    104.00       .00       .00       .00

          (BSTW(I),I=1,8)
     40.00     50.00     55.00     60.00    200.00       .00       .00       .00

          (CMTW(I),I=1,8)
       .03       .03       .03       .03       .03       .00       .00       .00

  ZU=  3.00  ZD=  3.00  ZC=   .00  GL=   .00  GS=   .00  VMP=   .00  SEDCON=   .00

  D50C=   .00  PORC=   .00  UWC=   .00  CNC= .0000  AFRC=   .00  COHC=    .0  UNFCC=   .00

  D50S=   .01  PORS=   .28  UWS=120.00  CNS= .0000  AFRS= 40.00  COHS= 712.0  UNFCS=107.00

  BR=  2.00  WC=  16.0  CRL=   12.0  SM= 11.00  D50DF=   .00  UNFCDF=   .00   BMX=   12.   BTMX=   12.

  DTH=  .020  DBG=  .001   H=   .1000   TEH=   20.0  ERR=   .50  FPT=   1.0  TPR=    .0

          (SPQ(I),I=1,8)
       .00     -1.05     -2.96     -5.43     -8.37    -11.69    -15.37    -19.37

          (SPH(I),I=1,8)
       .00       .15       .30       .45       .60       .75       .90      1.05


          AFRA=    .0   TH1= 65.00   H1= 50.90   TH2= 52.50   H2=175.87   TH3= 46.25   H3=608.50   SEDCON=   .50


1
```

I	T	DTH	KG	KC	QTOT	QTS	QB	SUB	BT	HY	HC	BO	PPP	HP	TWD	DH	DHH	KIT	AGL
1	.020	.0200	-1	0	0.	0.	0.	1.000	.2	103.1	105.8	.0	.0	.0	.00	.01	.00	0	.0
2	.270	.2500	-1	0	0.	0.	0.	1.000	.2	103.3	105.8	.0	.0	.0	100.25	.01	.00	0	.0
3	.520	.2500	-1	0	0.	0.	0.	1.000	.2	103.9	105.8	.0	.0	.0	100.25	.01	.00	0	.0
4	.770	.2500	-1	0	0.	0.	0.	1.000	.2	104.7	105.8	.0	.0	.0	100.25	.01	.00	0	.0
5	.790	.0200	-1	0	0.	0.	0.	1.000	.2	105.2	105.8	.0	.0	.0	100.25	.01	.00	0	.0
6	.810	.0200	-1	0	0.	0.	0.	1.000	.2	105.3	105.8	.0	.0	.0	100.25	.01	.00	0	.0
7	.830	.0200	-1	0	0.	0.	0.	1.000	.2	105.4	105.8	.0	.0	.0	100.25	.01	.00	0	.0
8	.850	.0200	-1	0	0.	0.	0.	1.000	.2	105.5	105.8	.0	.0	.0	100.25	.01	.00	0	.0
9	.870	.0200	-1	0	0.	0.	0.	1.000	.2	105.5	105.8	.0	.0	.0	100.25	.01	.00	0	.0
10	.890	.0200	-1	0	0.	0.	0.	1.000	.2	105.6	105.8	.0	.0	.0	100.25	.01	.00	0	.0
11	.910	.0200	-1	0	0.	0.	0.	1.000	.2	105.7	105.8	.0	.0	.0	100.25	.01	.00	0	.0
12	.930	.0200	-1	0	0.	0.	0.	1.000	.2	105.7	105.8	.0	.0	.0	100.25	.01	.00	0	.0
13	.950	.0200	-1	0	0.	0.	0.	1.000	.2	105.8	105.8	.0	.0	.0	100.25	.01	.00	0	.0
14	.970	.0200	1	0	0.	0.	0.	1.000	.7	105.9	105.8	.7	.3	1.1	100.25	.24	.24	1	.0
15	.992	.0220	1	0	1.	1.	0.	1.000	2.0	106.0	105.8	2.0	1.0	3.1	100.25	.64	.64	1	.0
16	1.014	.0220	1	0	3.	3.	2.	1.000	4.2	106.1	105.8	4.2	2.1	6.7	100.25	1.13	1.13	1	.0
17	1.036	.0220	1	0	5.	5.	4.	1.000	7.6	106.1	105.8	7.6	3.8	12.0	100.25	1.67	1.67	1	.0
18	1.056	.0200	1	0	6.	6.	9.	1.000	11.6	106.2	105.8	11.6	5.8	18.3	100.25	2.01	2.01	1	.0
19	1.058	.0018	2	0	157.	-3.	160.	1.000	11.6	106.2	103.5	11.6	25.1	2.3	100.25	2.41	2.42	11	.0
20	1.059	.0000	2	0	165.	-3.	167.	1.000	11.6	106.2	103.4	11.6	25.4	2.4	101.25	.10	.10	3	.0
21	1.059	.0000	2	0	174.	-3.	177.	1.000	11.6	106.2	103.3	11.6	25.7	2.5	101.25	.11	.11	1	.0
22	1.059	.0000	2	0	185.	-3.	188.	1.000	11.6	106.2	103.1	11.6	26.0	2.7	101.25	.13	.13	1	.0
23	1.059	.0001	2	0	198.	-3.	201.	1.000	11.6	106.2	103.0	11.6	26.4	2.8	101.25	.14	.14	2	.0
24	1.059	.0001	2	0	213.	-3.	216.	1.000	11.6	106.2	102.8	11.6	26.9	3.0	101.75	.17	.17	2	.0
25	1.059	.0001	2	0	231.	-2.	234.	1.000	11.6	106.2	102.6	11.6	27.4	3.2	101.75	.19	.19	2	.0
26	1.059	.0001	2	0	253.	-2.	255.	1.000	11.6	106.2	102.4	11.6	28.1	3.4	101.75	.22	.22	2	.0
27	1.059	.0001	2	0	279.	-2.	281.	1.000	11.6	106.2	102.2	11.6	28.8	3.6	101.75	.26	.26	2	.0
28	1.059	.0001	2	0	310.	-2.	312.	1.000	11.6	106.2	101.9	11.6	29.6	3.9	101.75	.30	.30	2	.0
29	1.059	.0001	2	0	347.	-2.	350.	1.000	11.6	106.2	101.5	11.6	30.6	4.3	101.75	.35	.35	2	.0
30	1.059	.0001	2	0	382.	-2.	384.	1.000	11.6	106.2	101.2	11.6	31.5	4.6	102.25	.31	.31	4	.0
31	1.059	.0001	2	0	410.	-2.	413.	1.000	11.6	106.2	101.0	11.6	32.2	4.8	102.25	.25	.25	5	.0
32	1.060	.0001	2	0	433.	-2.	435.	1.000	11.6	106.2	100.8	11.6	32.7	5.0	102.25	.20	.20	5	.0
33	1.060	.0001	2	0	451.	-2.	453.	1.000	11.6	106.2	100.6	11.6	33.2	5.2	102.25	.16	.16	5	.0
34	1.060	.0002	2	0	465.	-2.	467.	1.000	11.6	106.2	100.5	11.6	33.5	5.3	102.25	.12	.12	5	.0
35	1.060	.0002	2	0	476.	-2.	478.	1.000	11.6	106.2	100.4	11.6	33.8	5.4	102.25	.10	.10	5	.0
36	1.060	.0002	2	0	484.	-2.	486.	1.000	11.6	106.1	100.3	11.6	34.0	5.5	102.25	.08	.08	5	.0
37	1.060	.0002	2	0	491.	-2.	493.	1.000	11.6	106.1	100.3	11.6	34.2	5.5	102.75	.06	.06	5	.0
38	1.061	.0002	2	0	495.	-2.	498.	1.000	11.6	106.1	100.2	11.6	34.3	5.6	102.75	.05	.05	5	.0
39	1.061	.0003	2	0	499.	-2.	501.	1.000	11.6	106.1	100.2	11.6	34.4	5.6	102.75	.04	.04	4	.0
40	1.061	.0003	2	0	501.	-2.	503.	1.000	11.6	106.1	100.2	11.6	34.5	5.6	102.75	.03	.03	4	.0
41	1.062	.0003	2	0	503.	-2.	505.	1.000	11.6	106.1	100.1	11.6	34.6	5.7	102.75	.03	.03	4	.0
42	1.062	.0003	2	0	503.	-2.	505.	1.000	11.6	106.1	100.1	11.6	34.7	5.7	102.75	.02	.02	4	.0
43	1.062	.0004	2	0	503.	-2.	505.	1.000	11.6	106.0	100.1	11.6	34.7	5.7	102.75	.02	.02	4	.0
44	1.063	.0004	2	0	503.	-1.	504.	1.000	11.6	106.0	100.1	11.6	34.8	5.7	102.75	.02	.02	4	.0
45	1.063	.0004	2	0	501.	-1.	502.	1.000	11.6	106.0	100.1	11.6	34.8	5.7	102.75	.01	.01	4	.0
46	1.064	.0005	2	0	499.	-1.	500.	1.000	11.6	106.0	100.0	11.6	34.8	5.8	102.75	.01	.01	4	.0

47	1.064	.0005	2	0	497.	-1.	498.	1.000	11.6	105.9	100.0	11.6	34.9	5.8	102.75	.01	.01	4	.0
48	1.065	.0006	2	0	494.	-1.	495.	1.000	11.6	105.9	100.0	11.6	34.9	5.8	102.75	.01	.01	4	.0
49	1.065	.0007	2	0	490.	0.	491.	1.000	11.6	105.9	100.0	11.6	34.9	5.8	102.75	.01	.01	4	.0
50	1.066	.0007	2	0	486.	0.	487.	1.000	11.6	105.8	100.0	11.6	34.9	5.8	102.75	.01	.01	4	.0
I	T	DTH	KG	KC	QTOT	QTS	QB	SUB	BT	HY	HC	BO	PPP	HP	TWD	DH	DHH	KIT	AGL
51	1.067	.0008	2	0	482.	0.	482.	1.000	11.6	105.8	100.0	11.6	34.9	5.8	102.75	.00	.00	4	.0
52	1.068	.0009	2	0	477.	0.	477.	1.000	11.6	105.7	100.0	11.6	34.9	5.8	102.75	.00	.00	3	.0
53	1.069	.0010	2	0	471.	0.	471.	1.000	11.6	105.7	100.0	11.6	35.0	5.8	102.25	.00	.00	3	.0
54	1.070	.0011	2	0	464.	0.	464.	1.000	11.6	105.6	100.0	11.6	35.0	5.8	102.25	.00	.00	3	.0
55	1.071	.0012	2	0	457.	0.	457.	1.000	11.6	105.6	100.0	11.6	35.0	5.8	102.25	.00	.00	3	.0
56	1.072	.0013	2	0	450.	0.	450.	1.000	11.6	105.5	100.0	11.6	35.0	5.8	102.25	.00	.00	3	.0
57	1.074	.0014	2	0	441.	0.	441.	1.000	11.6	105.4	100.0	11.6	35.0	5.8	102.25	.00	.00	3	.0
58	1.075	.0015	2	0	432.	0.	432.	1.000	11.6	105.4	100.0	11.6	35.0	5.8	102.25	.00	.00	1	.0
59	1.077	.0017	3	0	423.	0.	423.	1.000	11.6	105.3	100.0	11.6	.0	2.1	102.25	.00	.00	1	.0
60	1.079	.0019	3	0	412.	0.	412.	1.000	11.6	105.2	100.0	11.6	.0	2.1	102.25	.00	.00	1	.0
61	1.081	.0021	3	0	401.	0.	401.	1.000	11.6	105.1	100.0	11.6	.0	2.0	102.25	.00	.00	1	.0
62	1.083	.0023	3	0	389.	0.	389.	1.000	11.6	105.0	100.0	11.6	.0	2.0	102.25	.00	.00	1	.0
63	1.086	.0025	3	0	377.	0.	377.	1.000	11.6	104.9	100.0	11.6	.0	2.0	102.25	.00	.00	1	.0
64	1.088	.0027	3	0	363.	0.	363.	1.000	11.6	104.8	100.0	11.6	.0	1.9	102.25	.00	.00	1	.0
65	1.091	.0030	3	0	349.	0.	349.	1.000	11.6	104.7	100.0	11.6	.0	1.9	102.25	.00	.00	2	.0
66	1.095	.0033	3	0	335.	0.	335.	1.000	11.6	104.5	100.0	11.6	.0	1.8	102.25	.00	.00	2	.0
67	1.098	.0036	3	0	320.	0.	320.	1.000	11.6	104.4	100.0	11.6	.0	1.8	102.25	.00	.00	2	.0
68	1.102	.0040	3	0	304.	0.	304.	1.000	11.6	104.2	100.0	11.6	.0	1.7	101.75	.00	.00	2	.0
69	1.107	.0044	3	0	287.	0.	287.	1.000	11.6	104.1	100.0	11.6	.0	1.7	101.75	.00	.00	2	.0
70	1.112	.0049	3	0	269.	0.	269.	1.000	11.6	103.9	100.0	11.6	.0	1.7	101.75	.00	.00	0	.0
71	1.117	.0053	3	0	250.	0.	250.	1.000	11.6	103.7	100.0	11.6	.0	1.5	101.75	.00	.00	2	.0
72	1.123	.0059	3	0	233.	0.	233.	1.000	11.6	103.6	100.0	11.6	.0	1.5	101.75	.00	.00	2	.0
73	1.129	.0065	3	0	216.	0.	216.	1.000	11.6	103.4	100.0	11.6	.0	1.4	101.75	.00	.00	2	.0
74	1.136	.0071	3	0	199.	0.	199.	1.000	11.6	103.2	100.0	11.6	.0	1.3	101.75	.00	.00	2	.0
75	1.144	.0078	3	0	183.	0.	183.	1.000	11.6	103.0	100.0	11.6	.0	1.3	101.75	.00	.00	2	.0
76	1.153	.0086	3	0	166.	0.	166.	1.000	11.6	102.8	100.0	11.6	.0	1.2	101.25	.00	.00	2	.0
77	1.162	.0095	3	0	150.	0.	150.	1.000	11.6	102.7	100.0	11.6	.0	1.1	101.25	.00	.00	2	.0
78	1.173	.0104	3	0	135.	0.	135.	1.000	11.6	102.5	100.0	11.6	.0	1.1	101.25	.00	.00	2	.0
79	1.184	.0114	3	0	121.	0.	121.	1.000	11.6	102.3	100.0	11.6	.0	1.0	101.25	.00	.00	2	.0
80	1.197	.0126	3	0	107.	0.	107.	1.000	11.6	102.1	100.0	11.6	.0	.9	101.25	.00	.00	2	.0
81	1.210	.0138	3	0	95.	0.	95.	1.000	11.6	102.0	100.0	11.6	.0	.9	101.25	.00	.00	2	.0
82	1.226	.0152	3	0	84.	0.	84.	1.000	11.6	101.8	100.0	11.6	.0	.8	101.25	.00	.00	2	.0
83	1.242	.0167	3	0	74.	0.	74.	1.000	11.6	101.7	100.0	11.6	.0	.7	100.75	.00	.00	2	.0
84	1.261	.0184	3	0	65.	0.	65.	1.000	11.6	101.5	100.0	11.6	.0	.7	100.75	.00	.00	2	.0
85	1.281	.0203	3	0	58.	0.	58.	1.000	11.6	101.4	100.0	11.6	.0	.6	100.75	.00	.00	2	.0
86	1.303	.0223	3	0	51.	0.	51.	1.000	11.6	101.3	100.0	11.6	.0	.6	100.75	.00	.00	2	.0
87	1.328	.0245	3	0	46.	0.	46.	1.000	11.6	101.2	100.0	11.6	.0	.6	100.75	.00	.00	2	.0

KTT= 0 I= 87 T= 1.33

OUTPUT SUMMARY

QBP	MAX OUTFLOW(CFS) THRU BREACH	505.
TP	TIME(HR) AT WHICH PEAK OUTFLOW OCCURS	1.06
QP	MAX TOTAL OUTFLOW(CFS) OCCURRING AT TIME TP	503.
TRS	DURATION(HR) OF RISING LIMB OF HYDROGRAPH	.03
TB	TIME(HR) AT WHICH SIGN. RISE IN OUTFLOW STARTS	1.04
BRD	FINAL DEPTH(FT) OF BREACH	5.80
BRW	TOP WIDTH(FT) OF BREACH AT PEAK BREACH FLOW	11.57
HU	ELEV(FT) OF TOP OF DAM	105.80
HY	FINAL ELEV(FT) OF RESERVOIR WATER SURFACE	101.21
HC	FINAL ELEV(FT) OF BOTTOM OF BREACH	100.000
AGL	ACUTE ANGLE THAT BREACH SIDE MAKES WITH VERTICAL AT QBP	.000
QO	OUTFLOW (CFS) AT T=0.0	.0000
Z	SIDE SLOPE OF BREACH (FT/FT) AT PEAK BREACH FLOW	.00
TFH	TIME OF FAILURE (HR) WHICH IS LINEAR EQUIVALENT OF TRS OBTAINED BY USING SIMPLIFIED DAM-BREAK DISCHARGE EQUATION	.01
TFHI	TIME OF FAILURE (HR) WHICH IS LINEAR EQUIVALENT OF TRS OBTAINED BY INTEGRATING QB VS TIME FROM T=0 TO T=TP	.01
BO	BOTTOM WIDTH (FT) OF BREACH AT PEAK BREACH FLOW	11.57

1

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0TIME -2.0    48.0      98.0     148.0     198.0     248.0     298.0     348.0     398.0     448.0     498.0     DISCHARGE
    .830*         .         .         .         .         .         .         .         .         .         .          0.
    .850*         .         .         .         .         .         .         .         .         .         .          0.
    .870*         .         .         .         .         .         .         .         .         .         .          0.
    .890*         .         .         .         .         .         .         .         .         .         .          0.
    .910*         .         .         .         .         .         .         .         .         .         .          0.
    .930*         .         .         .         .         .         .         .         .         .         .          0.
    .950*         .         .         .         .         .         .         .         .         .         .          0.
    .970*         .         .         .         .         .         .         .         .         .         .          0.
    .990*         .         .         .         .         .         .         .         .         .         .          1.
   1.010*         .         .         .         .         .         .         .         .         .         .          3.
   1.030*         .         .         .         .         .         .         .         .         .         .          4.
   1.050$*        .         .         .         .         .         .         .         .         .         .          6.
   1.070$         .         .         .         .         .         .         .         .         . *       .        463.
   1.090$         .         .         .         .         .         .         .*        .         .         .        356.
   1.110$         .         .         .         .         .    *    .         .         .         .         .        275.
   1.130$         .         .         .         .  *      .         .         .         .         .         .        214.
   1.150$         .         .         .   *     .         .         .         .         .         .         .        171.
   1.170$         .         .      *  .         .         .         .         .         .         .         .        139.
   1.190$         .         . *       .         .         .         .         .         .         .         .        114.
   1.210$         .        *.         .         .         .         .         .         .         .         .         96.
   1.230$         .     *   .         .         .         .         .         .         .         .         .         81.
   1.250$         .   *     .         .         .         .         .         .         .         .         .         70.
   1.270$         . *       .         .         .         .         .         .         .         .         .         62.
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Table C.7. SIMBA input file for ARS test 1.

```
BREACH    01/01/2005
WHA
WDC
OPTIONS   00101
IHW
IHH
USL       3
DSL       3
HDM       5.8
CWD       16
CEL       105.8
BKD       120
UDS       711
KDI       0.022
CSS       .3
DWD       6
NSS       3
ELE       103.07
HCMODEL   6
STRUCTURE C
          100       0
          100.5     5837
          101       13591
          101.5     22869
          102       33323
          102.5     44649
          103       56628
          103.5     69086
          104       81893
          104.5     95048
          105       108552
          105.5     122491
          106       136953
          106.5     152198
          107       168490
          107.5     186088
ENDTABLE
HYD
          0.00833333
          0.000     0
          0.017     2.89327808
          0.033     7.94268904
          0.050     11.8091886
          0.067     14.6964627
          0.083     15.7110796
          0.100     16.2279300
          0.117     16.7510745
          0.133     17.3337450
          0.150     17.9779305
          0.167     18.4123031
          0.183     18.9607585
          0.200     19.6828024
          0.217     20.2451300
          0.233     20.7563242
          0.250     21.2147498
          0.267     21.5031829
          0.283     21.8512411
          0.300     22.3185945
          0.317     22.5536698
          0.333     23.0859826
          0.350     23.5032386
          0.367     23.8631292
          0.383     24.4068288
          0.400     24.8939916
          0.417     25.3232356
          0.433     25.5697605
          0.450     25.9412368
          0.467     26.1900105
          0.483     26.6275186
          0.500     26.8158591
          0.517     27.0677590
          0.533     27.2572672
          0.550     27.5107208
          0.567     27.7650596
          0.583     27.8925602
          0.600     28.1482228
          0.617     28.2763843
          0.633     28.4690385
          0.650     28.5977490
          0.667     28.7266787
          0.683     28.9851947
          0.700     29.1147805
          0.717     29.3095683
          0.733     29.5700477
          0.750     29.6353036
          0.767     29.7659781
          0.783     29.8313968
          0.800     29.8968697
          0.817     30.0279781
          0.833     30.1593032
          0.850     30.2908445
          0.867     30.3566962
          0.883     30.4226020
          0.900     30.5545754
          0.917     30.6867644
          0.933     30.8191689
          0.950     30.9517886
          0.967     31.0846232
          0.983     31.1511211
          1.000     31.2176727
          1.017     31.2842778
          1.033     31.3509366
          1.050     31.4176490
          1.067     31.4844149
          1.083     31.5512343
          1.100     31.6181073
          1.117     31.6850337
          1.133     31.6850337
          1.150     31.7520135
          1.167     31.7520135
          1.183     31.8190468
          1.200     31.8861334
          1.217     31.9532734
          1.233     32.0204667
          1.250     32.0877133
          1.267     32.0877133
          1.283     32.0877133
          1.300     32.1550132
```

1.317	32.2223664
1.333	32.2223664
1.350	32.2897727
1.367	32.3572323
1.383	32.4247450
1.400	32.4247450
1.417	32.4247450
1.433	32.4247450
1.450	32.4247450
1.467	32.4923109
1.483	32.4923109
1.500	32.4923109
1.517	32.4923109
1.533	32.5599298
1.550	32.5599298
1.567	32.5599298
1.583	32.6276019
1.600	32.6276019
1.617	32.6276019
1.633	32.6953270
1.650	32.6953270
1.667	32.6953270
1.683	32.7631051
1.700	32.7631051
1.717	32.8309363
1.733	32.8309363
1.750	32.8309363
1.767	32.8309363
1.783	32.8309363
1.800	32.8988204
1.817	32.8988204
1.833	32.8988204
1.850	32.8988204
1.867	32.8988204
1.883	32.9667575
1.900	32.9667575
1.917	32.9667575
1.933	32.9667575
1.950	32.9667575
1.967	33.0347475
1.983	33.0347475
2.000	33.0347475
2.017	33.0347475
2.033	33.0347475
2.117	33.1027904
2.200	33.1027904
2.283	33.1027904
2.367	33.1027904
2.450	33.1027904
2.533	33.1027904
2.617	33.1027904
2.700	33.1027904
2.783	33.1027904
2.867	33.1027904
2.950	33.1027904
3.033	33.1027904
3.117	33.1027904
3.200	33.1027904
3.283	33.1027904
3.367	33.1027904
3.450	33.1027904
3.533	33.1027904
3.617	33.1027904
3.700	33.1027904
3.783	33.1027904
3.867	33.1027904
3.950	33.1027904
4.033	33.1027904
5.033	33.1027904
6.033	33.3754904
7.033	33.6490346
8.033	33.5121571
9.033	33.5805695
10.033	33.5805695
11.033	33.5121571
12.033	33.6490346
13.033	33.7861228
14.033	33.7861228
15.033	33.6490346
16.033	33.5121571
17.033	33.5121571
18.033	33.6490346
19.033	33.7175524
19.117	33.7175524
19.200	33.7175524
19.283	33.7175524
19.367	33.7175524
19.450	33.7175524
19.533	33.7175524
19.617	33.7175524
19.700	33.7175524
19.783	33.7175524
19.867	33.7175524
19.950	33.7175524
20.033	33.7175524
20.117	33.6490346
20.200	33.6490346
20.217	33.6490346
20.233	33.6490346
20.250	33.6490346
20.267	33.6490346
20.283	33.6490346
20.300	33.6490346
20.317	33.6490346
20.333	33.6490346
20.350	33.6490346
20.367	33.6490346
20.383	33.6490346
20.400	33.6490346
20.417	33.6490346
20.533	0

ENDTABLE

Table C.8. SIMBA output file for ARS test 2, reduced.

Time	Qin	Qout	Qb	Qd	El	HC Pos	Attack	Hh	Width	Hc	
0	0	0	0	0	103.11	33.4	0	0	0	105.8	
0.25	21	0	0	0	103.632		33.4	0	0	0	105.8
0.5	26.7	0	0	0	104.459		33.4	0	0	0	105.8
0.75	29.6	0	0	0	105.386		33.4	0	0	0	105.8
1	31.2	7	0	6.9	106.271		33.4	0	0.002	0.004	105.8
1.25	32.1	22	0	22.1	106.74	33.4	0.05	0.017	0.025	105.8	
1.5	32.5	29	0	29.2	106.904		33.4	0.14	0.039	0.056	105.8
1.75	32.8	32	0	31.4	106.954		33.4	0.24	0.063	0.089	105.8
2	33	33	0	32.1	106.97	33.4	0.34	0.087	0.123	105.8	
3	33.1	33	1	32.1	106.98	33.4	0.74	0.186	0.261	105.8	
4	33.1	33	2	31.5	106.98	33.4	1.13	0.285	0.399	105.8	
5	33.1	33	2	31	106.98	33.4	1.52	0.383	0.538	105.8	
6	33.4	33	3	30.7	106.986		33.4	1.93	0.482	0.676	105.8
7	33.6	34	3	30.4	106.991		33.4	2.34	0.582	0.816	105.8
8	33.5	34	4	29.7	106.989		33.4	2.73	0.681	0.955	105.8
9	33.6	34	4	29.2	106.99	33.4	3.13	0.781	1.094	105.8	
10	33.6	34	4	29.1	106.99	33.388	3.53	0.88	1.122	105.8	
11	33.5	34	5	29	106.989		33.373	3.92	0.98	1.138	105.8
12	33.6	34	5	29	106.991		33.358	4.34	1.08	1.153	105.8
13	33.8	34	5	29.1	106.994		33.344	4.75	1.179	1.166	105.8
14	33.8	34	5	29	106.994		33.332	5.16	1.279	1.178	105.8
15	33.7	34	5	28.9	106.991		33.322	5.54	1.379	1.189	105.8
16	33.5	34	5	28.7	106.989		33.312	5.92	1.479	1.198	105.8
17	33.5	34	5	28.7	106.989		33.304	6.32	1.578	1.207	105.8
18	33.6	34	5	28.8	106.991		33.296	6.74	1.678	1.214	105.8
19	33.7	34	5	28.8	106.993		33.289	7.15	1.777	1.221	105.8
20	33.7	34	5	28.8	106.993		33.283	7.55	1.877	1.228	105.8
20.25	33.6	34	5	28.7	106.991		33.281	7.64	1.902	1.229	105.8
20.5	12	30	4	25.4	106.913		33.28	6.99	1.927	1.231	105.8
20.75	0	11	2	9.1	106.422		33.28	2.95	1.945	1.231	105.8
21	0	5	1	4.3	106.197		33.28	1.51	1.956	1.231	105.8
21.25	0	3	1	2.4	106.08	33.28	0.9	1.963	1.231	105.8	
21.5	0	2	0	1.6	106.011		33.28	0.59	1.968	1.231	105.8
21.75	0	1	0	1	105.964		33.28	0.4	1.971	1.231	105.8
22	0	1	0	0.7	105.932		33.28	0.29	1.973	1.231	105.8
22.25	0	1	0	0.6	105.909		33.28	0.22	1.975	1.231	105.8
22.5	0	1	0	0.4	105.892		33.28	0.17	1.976	1.231	105.8
22.75	0	0	0	0.3	105.879		33.28	0.14	1.977	1.231	105.8
23	0	0	0	0.3	105.87	33.28	0.11	1.978	1.231	105.8	
23.25	0	0	0	0.2	105.862		33.28	0.09	1.978	1.231	105.8
23.5	0	0	0	0.2	105.856		33.28	0.08	1.978	1.231	105.8
23.75	0	0	0	0.2	105.85	33.28	0.07	1.978	1.231	105.8	
24	0	0	0	0.1	105.846		33.28	0.06	1.978	1.231	105.8

SUMMARY:
OTBegins 0.867
HCAdv 9.117
TauSwitch 0.000
BreachSt 0.000
HCDown 0.000
BrEnd 0.000

APPENDIX D

SYNTHETIC DATA SET DEVELOPMENT AND MODEL INPUT AND OUTPUT FILES

Table D.1. Summary of failed dams data used in figures and height-storage relation development.

[1]Height of dam crest or water surface elevation at failure relative to dam base
[2]Some appear in multiple sources, most recent is used in study. Data from Wahl (1998) are those he judged to be "Best Reliable Information." Kalkanis indicates Kalkanis et al. 1986

Name and/or nearest city	Location	Head[1]	Dam height, h_d	Storage	Peak breach discharge, Q_p	Storage curve	Present in Figures		References[2]
		ft	ft	ac ft	cfs		1.1,1.2,	3.2	
Apishapa	Colorado, USA	112	112	18241	241905	Y	Y	Y	Wahl 1998
Baldwin Hills	California, USA	233	233	892	39906	Y	Y	Y	Wahl 1998
Boydstown	Pennsylvania, USA	29	29	290	2300	Y	Y	Y	Kalkanis
Bradfield	England	95	95	2594	40612	Y	Y	Y	Wahl 1998
Break Neck Run	USA	23	23	40	325	Y	Y	Y	Wahl 1998
Buffalo Creek	West Virginia, USA	46	46	392	50147	Y	Y	Y	Wahl 1998
Bullock Draw Dike	Utah, USA	19	70	916	-	Y	Y		Wahl 1998
Caney Coon Creek	Oklahoma, USA	15	15	1070	600	Y	Y	Y	Kalkanis
Canyon Lake	South Dakota, USA	20	20	799	-	Y	Y		Wahl 1998
Castlewood	Oklahoma, USA	70	70	3429	126073	Y	Y	Y	Wahl 1998
Cheaha Creek, USA	USA	23	23	56	300	Y	Y	Y	Wahl 1998
Cherokee Sandy	Oklahoma, USA	17	39	360	500	Y	Y	Y	Kalkanis
Coedty	England	36	29	251	-	Y	Y		Wahl 1998
Colonial #4	Pennsylvania, USA	33	174	31	1730	Y	Y	Y	Kalkanis
Dam Site #8	Mississippi, USA	15	32	705	18010	Y	Y	Y	Kalkanis
Davis Reservoir	California, USA	39	34	47000	28005	Y	Y	Y	Wahl 1998
DMAD	Utah, USA	29	40	15971	36021	Y	Y	Y	Wahl 1998
Elk City	Oklahoma, USA	30	41	600	-	Y	Y		Wahl 1998
Euclides de Cunha	Brazil	174	20	11026	36021	Y	Y	Y	Wahl 1998
Frankfurt (Main)	Germany	32	32	284	2790	Y	Y	Y	Wahl 1998
Fred Burr	Montana, USA	34	63	610	23100	Y	Y	Y	Wahl 1998
French Landing	Michigan, USA	28	40	-	32807			Y	Wahl 1998
Frenchman	Montana, USA	41	22	17025	50147	Y	Y	Y	Wahl 1998

Name and/or nearest city	Location	Head[1]	Dam height, h_d	Storage	Peak breach discharge, Q_p	Storage curve	Present in Figures		References[2]
Goose Creek	South Carolina, USA	20	20	8594	19953	Y	Y	Y	Wahl 1998
Grand Rapids	Michigan, USA	25	220	178	65014	Y	Y	Y	Wahl 1998
Granite Creek	Alaska, USA	-	85	-	65014			Y	Kirkpatrick
Hatchtown	Utah, USA	63	25	11999	108769	Y	Y	Y	Wahl 1998
Hatfield	USA	22	125	9972	120070	Y	Y	Y	Wahl 1998
Haymaker	Montana, USA	16	38	300	950	Y	Y	Y	Kalkanis
Hell Hole	California, USA	220	48	24808	259916	Y	Y	Y	Wahl 1998
Horse Creek #2	Colorado, USA	41	43	3890	11000	Y	Y	Y	Wahl 1998
Iowa Beef Processors,	Washington, USA	15	15	270	-	Y	Y		Wahl 1998
Johnston City	Illinois, USA	14	42	466	-	Y	Y		Wahl 1998
Kaddam	India	41	86	173493	-	Y	Y		Wahl 1998
Kelley Barnes	Georgia, USA	38	38	409	24014	Y	Y	Y	Wahl 1998
Kendall Lake Dam, S.C.	South Carolina, USA	18	18	590	-	Y	Y		Wahl 1998
Lake Avalon	New Mexico, USA	48	48	6283	81930	Y	Y	Y	Wahl 1998
Lake Barcroft	Virginia, USA	69	37	2529	-	Y	Y		Wahl 1998
Lake Francis	California, USA	50	50	701	-	Y	Y		Wahl 1998
Lake Latonka	Pennsylvania, USA	43	70	1289	10241	Y	Y	Y	Wahl 1998
Lake Tanglewood	Texas, USA	55	55	3936	47700	Y	Y	Y	Kalkanis
Laurel Run	Pennsylvania, USA	42	43	312	37080	Y	Y	Y	Wahl 1998
Lawn Lake	Colorado, USA	22	26	-	18010			Y	Wahl 1998
Little Deer Creek	Utah, USA	86	86	1403	46969	Y	Y	Y	Wahl 1998
Little Wewoka	Oklahoma, USA	31	52	800	1500	Y	Y	Y	Kalkanis
Lower Latham	Colorado, USA	19	18	5740	18000	Y	Y	Y	Wahl 1998
Lower Otay	California, USA	135	116	39968	-	Y	Y		Wahl 1998
Lower Reservoir	Maine, USA	32	19	490	5560	Y	Y	Y	Kalkanis
Lower Two Medicine	Montana, USA	37	37	15890	63566	Y	Y	Y	Wahl 1998
Lyman, Ariz.	Arizona, USA	65	65	40130	-	Y	Y		Wahl 1998
Lynde Brook, Mass.	Massachusetts, USA	41	41	2043	-	Y	Y		Wahl 1998
Machhu II	Gujarat, India	197	197	89178	-	Y	Y		Wahl 1998
Malpasset	Frejus, France	200	115	17800	1000000	Y	Y	Y	Kalkanis
Mammoth	USA	70	28	11026	88993	Y	Y	Y	Wahl 1998

Name and/or nearest city	Location	Head[1]	Dam height, h_d	Storage	Peak breach discharge, Q_p	Storage curve	Present in Figures		References[2]
Middle Clear Boggy	Oklahoma, USA	15	100	360	1300	Y	Y	Y	Kalkanis
Mill River	Massachusetts, USA	43	34	2027	58093	Y	Y	Y	Wahl 1998
Murnion	Montana, USA	14	14	260	618	Y	Y	Y	Kalkanis
Nanaksagar	Punjab, India	52	52	170250	342552	Y	Y	Y	Wahl 1998
North Branch Tributary	Pennsylvania, USA	18	18	-	1038			Y	Wahl 1998
Oros	Ceará, Brazil	116	116	526964	340080	Y	Y	Y	Wahl 1998
Otto Run	USA	19	19	-	2119			Y	Wahl 1998
Owl Creek	Oklahoma, USA	16	6	97	1100	Y	Y	Y	Kalkanis
Peter Green	New Hampshire,	13	13	16	156	Y	Y	Y	Kalkanis
Prospect	Colorado, USA	12	189	2880	2100	Y	Y	Y	Wahl 1998
Rito Manzanares	New Mexico, USA	24	305	20	-	Y	Y		Wahl 1998
Salles Oliveira	Brazil	115	115	20997	254266	Y	Y	Y	Wahl 1998
Sandy Run	Pennsylvania, USA	28	28	46	15362	Y	Y	Y	Wahl 1998
Schaeffer	Colorado, USA	100	100	3178	158916	Y	Y	Y	Wahl 1998
Sheep Creek	USA	56	56	1159	-	Y	Y		Wahl 1998
Sherburne, USA	USA	34	34	34	33902	Y	Y	Y	Wahl 1998
Sinker Creek, USA	USA	70	70	2700	-	Y	Y		Wahl 1998
Site Y-30-95	Mississippi, USA	25	25	115	5100	Y	Y	Y	Kalkanis
Site Y-31A-5	Mississippi, USA	31	31	313	1306	Y	Y	Y	Kalkanis
Site Y-36-25	Mississippi, USA	32	32	29	75	Y	Y	Y	Kalkanis
South Fork Tributary	Pennsylvania, USA	-	6		4308			Y	Wahl 1998
Southfork Dam,	Pennsylvania, USA	125	26	15322	300175	Y	Y	Y	Wahl 1998
Spring Lake	Rhode Island, USA	18	18	109	-	Y	Y		Wahl 1998
St. Francis	California, USA	185	185	38000	600000	Y	Y	Y	Kalkanis
Stevens Dam	Pennsylvania, USA	14	14	64	209	Y	Y	Y	Kalkanis
Swift	Montana, USA	189	189	30000	880995	Y	Y	Y	Wahl 1998
Teton	Idaho, USA	305	305	288614	2299691	Y	Y	Y	Wahl 1998
Upper Clear Bog	Oklahoma, USA	20	20	700	2500	Y	Y	Y	Kalkanis
Upper Red Rock	Oklahoma, USA	15	15	200	300	Y	Y	Y	Kalkanis
Wheatland Reservoir	Wyoming, USA	40	45	9300	20000	Y	Y	Y	Wahl 1998
Winston	North Carolina, USA	24	24	538	-	Y	Y		Wahl 1998

Equivalent crest length solution development for synthetic dams set

Begin with routing equation, no inflow.

(1) $\frac{2S_1}{\Delta t} - O_1 = \frac{2S_2}{\Delta t} + O_2$

Discharge is defined by broad crested weir equation.

(2) $O = CL(h - h_d)^{3/2}$

Storage is defined by hypsometric function.

(3) $S = \beta h_d^{(\alpha-m)h^m}$

Substitute (2) and (3) into (1):

(4) $\frac{\beta h_d^{\alpha-m} \cdot h_1^m}{\Delta t} - CL(h_1 - h_d)^{\frac{3}{2}} = \frac{\beta h_d^{\alpha-m} h_2^m}{\Delta t} + CL(h_2 - h_d)^{\frac{3}{2}}$

(5) $\frac{2(\beta h_d^{\alpha-m} h_1^m)}{\Delta t} - CL(h_1 - h_d)^{3/2} = \frac{2(\beta h_d^{\alpha-m} h_2^m)}{\Delta t} + CL(h_2 - h_d)^{3/2}$

(6) $\frac{2(\beta h_d^{\alpha-m} h_1^m)}{\Delta t} - \frac{2(\beta h_d^{\alpha-m} h_2^m)}{\Delta t} = CL(h_1 - h_d)^{3/2} - CL(h_2 - h_d)^{3/2}$

(7) $\frac{2\beta}{\Delta t} h_d^{\alpha-m}(h_1^m - h_2^m) = CL\left[(h_1 - h_d)^{3/2} - (h_2 - h_d)^{3/2}\right]$

Solve for L.

(8) $L = \frac{2\beta h_d^{\alpha-m}(h_1^m - h_2^m)}{C\Delta t\left[(h_1-h_d)^{3/2} - (h_2-h_d)^{3/2}\right]}$

Define boundary conditions.

(9) Let $h_1 = h_{t=0} = h_d + 1$

(10) Let $h_2 = h_{t=\infty} = h_d$

Evaluate at boundary conditions to remove some terms:

(11) $L = \frac{2\beta h_d^{\alpha-m}((h_d+1)^m - h_d^m)}{C\Delta t\left[\left((h_d+1)-h_d\right)^{3/2} - (h_d-h_d)^{3/2}\right]}$

(12) $L = \frac{2\beta h_d^{\alpha-m}((h_d+1)^m - h_d^m)}{C\Delta t\left[(1)^{3/2} - (0)^{3/2}\right]}$

(13) $L = \frac{2\beta h_d^{\alpha-m}((h_d+1)^m - h_d^m)}{C\Delta t}$

Express as ratio of length of dam *b* to dam *a*.

(14) $\frac{L_b}{L_a} = \frac{2\beta_b h_{d_b}^{\alpha_b - m_b}\left(\left(h_{d_b}+1\right)^{m_b} - h_{d_b}^{m_b}\right)/C\Delta t}{2\beta_a h_{d_a}^{\alpha_a - m_a}\left(\left(h_{d_a}+1\right)^{m_a} - h_{d_a}^{m_a}\right)/C\Delta t}$

Cancel like terms.

(15) $\frac{L_b}{L_a} = \frac{\beta_b h_{d_b}^{\alpha_b - m_b}\left(\left(h_{d_b}+1\right)^{m_b} - h_{d_b}^{m_b}\right)}{\beta_a h_{d_a}^{\alpha_a - m_a}\left(\left(h_{d_a}+1\right)^{m_a} - h_{d_a}^{m_a}\right)}$

Solve for length of dam *b*, L_b.

(16) $$L_b = L_a \frac{\beta_b h_{d_b}^{\alpha_b - m_b}\left(\left(h_{d_b}+1\right)^{m_b} - h_{d_b}^{m_b}\right)}{\beta_a h_{d_a}^{\alpha_a - m_a}\left(\left(h_{d_a}+1\right)^{m_a} - h_{d_a}^{m_a}\right)}$$

Numerical Solution to determine equivalent crest lengths.

Volume at crest determined by

$$V_c = \beta h_d^{\alpha}$$

where $V_c = storage\ volume\ at\ crest\ elevation, ft^3$,

$h_d = height\ of\ dam\ relative\ to\ dame\ base, ft$, and

$\alpha, \beta = constants\ determined\ by\ regression.$

Stage-storage defined by

$$V = \beta h_d^{\alpha - m} h^m$$

where $V =$ volume, ft^3,

$h =$ water surface elevation, relative to dam base, ft, and

$m =$ shape factor, usually $1 < m \leq 3$.

Discharge calculated using broad-crested weir equation

$Q = CLH^{3/2}$,

where $Q =$ discharge, $ft^3\ s^{-1}$

$C =$ weir coefficient, $ft^{1/2}\ s^{-1}$

$L =$ crest length, ft, and

$H =$ water surface elevation relative to crest (i.e., head), ft.

Model runs are initiated with $h = h_d + 1\ ft$. Volume of water above crest changes with relative storage, height, and reservoir shape. While all simulations begin with the same unit discharge, different drawdowns result from the wide range of storages if crest length is held constant.

The following numerical solution was developed first and applied using a spreadsheet program. Calculations were later verified against the analytical solution.

Table D.2. Numerical solution calculations equivalent crest length by time step.

t	Q	H	h	V_{AC}
0	$3LH^{3/2}$	$h - h_d$	$h_d + 1$	$\beta h_d^{\alpha-m}(h^m - h_d^m)$
$0 + 1$			$\left(\frac{V_{AC}}{\beta h_d^{\alpha-m}} + h_d^m\right)^{1/m}$	$V_{AC_0} - (t_{0+1} - t_0)Q_0$
j				$V_{AC_{j-1}} - (t_j - t_{j-1})\left(Q_{j-1} + \frac{Q_{j-1} - Q_{j-2}}{2}\right)$

Where $t = time, s,$

V_{AC} = volume above crest, ft^3, and

j = index.

Length was arbitrarily set for one case. Crest lengths of subsequent dams were made equivalent to the first by solving for the crest length that produced the lowest sum or errors for H for 12 hours of drawdown at 0.1-hr intervals.

Table D.3. Excerpt of spreadsheet employing numerical solution to match drawdown of synthetic dams A and B.

		shape	m	3		shape	m	1		
	coefficients	C*H^i	C	0.0365	L	C*H^d	C	52.719	U	Computation
			d	1.8757			d	1.9341		check:
Dam			A				B			
	hd =	5	height of dam		hd =	400	height of dam		2.096090406	appoximation of
	L =	0.2	weir length		L =	4974.35	weir length		0.20151294	VAC =
										23690
t	Q	H	h2	VAC	Q	H	h2	VAC		
hr	cfs	ft	ft	ft^3	cfs	ft	ft	ft^3	$(H_a-H_b)^2$	
0	0.6	1.000	6	23690	15420.5	1.000	401	618926778	0	
0.1	0.6	0.992	5.992051	23467	15213.5	0.991	400.991	613375401	1.0588E-06	221.871971
0.2	0.6	0.984	5.984223	23248	15011.6	0.982	400.9822	607935805	4.06038E-06	219.2413683
0.3	0.6	0.976	5.976467	23031	14813.2	0.974	400.9736	602567990	8.83549E-06	216.6532914
0.4	0.6	0.969	5.968783	22817	14618.3	0.965	400.965	597270953	1.52221E-05	214.0991784
0.5	0.6	0.961	5.96117	22606	14426.8	0.957	400.9566	592043452	2.30667E-05	211.5786284
0.6	0.6	0.954	5.953627	22397	14238.6	0.948	400.9482	586884278	3.22235E-05	209.0911968
0.7	0.6	0.946	5.946154	22190	14053.7	0.940	400.94	581792243	4.25544E-05	206.6364443
0.8	0.6	0.939	5.93875	21986	13872.0	0.932	400.9319	576766188	5.39287E-05	204.2139365
0.9	0.6	0.931	5.931414	21784	13693.4	0.924	400.9239	571804979	6.62224E-05	201.8232444
1	0.6	0.924	5.924146	21584	13517.8	0.916	400.916	566907504	7.93184E-05	199.4639438
1.1	0.5	0.917	5.916946	21387	13345.3	0.908	400.9081	562072677	9.31061E-05	197.1356154
1.2	0.5	0.910	5.909812	21192	13175.7	0.900	400.9004	557299433	0.000107481	194.8378452
1.3	0.5	0.903	5.902745	21000	13008.9	0.893	400.8928	552586732	0.000122345	192.5702238
1.4	0.5	0.896	5.895742	20810	12844.9	0.885	400.8853	547933554	0.000137605	190.3323469
1.5	0.5	0.889	5.888805	20622	12683.7	0.878	400.8779	543338900	0.000153173	188.1238149

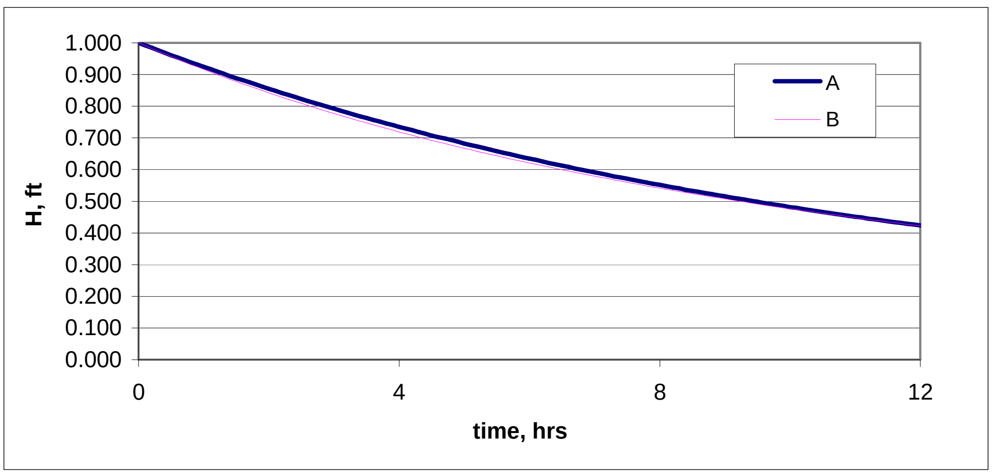

Figure D.1. Plot of drawdown , height, *H*, versus time for dams A and B after solving for lowest sum of squares of error.

Table D.4. Equivalent crest lengths for synthetic dams set as found by analytical and numerical methods and per cent difference in numerical solution relative to analytical solution.

	Baseline & material rate variations	Varied parameter			
		m		Vs	
h_d-S curve	U	U	U	R	L
a_b	1.934	1.934	1.934	1.905	1.876
b_b	52.7	52.7	52.7	1.388	0.0365
m_b	3	1	2	3	3
h_d, ft	Crest Length by Analytical Solution, ft				
5	320	87	192	8.0	0.20
10	550	167	350	13.6	0.33
20	1,000	320	650	24	0.58
50	2,300	750	1,510	54	1.26
100	4,300	1,430	2,900	100	2.3
200	8,200	2,700	5,500	186	4.2
400	15,700	5,200	10,500	350	7.7
h_d, ft	Crest Length by Numerical Solution (for 12 hours), ft				
5	320	83	190	8.0	0.20
10	540	160	340	13.3	0.33
20	970	300	630	23	0.56
50	2,200	710	1,440	52	1.21
100	4,100	1,360	2,700	95	2.2
200	7,900	2,600	5,200	177	4.0
400	15,000	5,000	10,000	330	7.3
h_d, ft	difference, %				
5	-0.1	-4.8	-2.5	0.4	0.0
10	-2.2	-3.9	-2.8	-2.0	-1.1
20	-3.4	-5.7	-3.4	-4.9	-4.0
50	-4.3	-5.2	-4.8	-3.4	-4.2
100	-4.5	-5.0	-6.1	-4.8	-4.1
200	-4.7	-4.9	-5.2	-4.8	-4.5
400	-4.7	-4.3	-4.4	-5.0	-4.8

Table D.5. Elevation versus volume and elevation versus area for the synthetic baseline of synthetic dams set.

$$\frac{V}{V_S} = \left[\frac{h}{h_d}\right]^m$$

Walder and O'Connor, 1997

$$V_S = \beta h_d^{\alpha}$$

Storage vs Height curve

$$V = \beta h_d^{\alpha - m} h^m$$

Stage-storage

$$A = \frac{m}{h} \beta h_d^{\alpha - m} h^m$$

Stage-area

let m = 3, β = 52.7, α = 1.9

h in ft, v in ac-ft

hd													
5		10		20		50		100		200		400	
h	v	h	v	h	v	h	v	h	v	h	v	h	v
0.0	0	0	0	0	0	0	0	0	0	0	0	0	0
0.5	1.2	1	4.5	2	17.3	5	101.8	10	389.2	20	1487.3	40	5683.4
1.0	9.5	2	36.2	4	138.5	10	814.8	20	3113.6	40	11898.1	80	45467.5
1.5	32	3	122.3	6	467.4	15	2749.8	30	10508.3	60	40156.2	120	153452.9
2.0	75.9	4	289.9	8	1107.8	20	6518.2	40	24908.5	80	95185.2	160	363740.3
2.5	148.2	5	566.2	10	2163.7	25	12730.8	50	48649.4	100	185908.5	200	710430.2
3.0	256	6	978.4	12	3738.9	30	21998.8	60	84066.1	120	321249.9	240	1227623
3.5	406.6	7	1553.7	14	5937.2	35	34933.3	70	133493.9	140	510133	280	1949420
4.0	606.9	8	2319.2	16	8862.6	40	52145.3	80	199267.8	160	761481.3	320	2909922
4.5	864.1	9	3302.1	18	12618.8	45	74245.9	90	283723.1	180	1084219	360	4143229
5.0	1185.3	10	4529.7	20	17309.7	50	101846.3	100	389194.9	200	1487268	400	5683442
6.0	2048.3	11	6029	21	20038.1	51	108080.1	101	400987.9	201	1509689	401	5726174
7.0	3252.6	12	7827.3	22	23039.2	52	114563.2	102	413016.8	202	1532334	402	5769120

h in ft, a in ac

hd													
5		10		20		50		100		200		400	
h	a	h	a	h	a	h	a	h	a	h	a	h	a
0	0	0	0	0	0	0	0	0	0	0	0	0	0
0.9	23.0	1.6	34.8	3	58.4	7.3	130.3	14.4	242.1	28.7	459.4	57.3	874.7
1.8	92.2	3.2	139.2	6	233.7	14.6	521.0	28.8	968.4	57.4	1837.6	114.6	3498.8
2.7	207.4	4.8	313.1	9	525.8	21.9	1172.3	43.2	2179.0	86.1	4134.5	171.9	7872.4
3.6	368.7	6.4	556.6	12	934.7	29.2	2084.1	57.6	3873.8	114.8	7350.3	229.2	13995.3
4.5	576.1	8.0	869.7	15	1460.5	36.5	3256.4	72.0	6052.8	143.5	11484.8	286.5	21867.6
5.4	829.6	9.6	1252.4	18	2103.1	43.8	4689.3	86.4	8716.0	172.2	16538.1	343.8	31489.4
6	1024.1	11	1644.3	21	2862.6	51	6357.7	101	11910.5	201	22532.7	401	42839.2

Table D.6. NWSB input file for synthetic base case; h_d = 50 ft, Storage *UP*, shape m = 3, D_{50} = 5mm.

```
BASE CASE:  H = 50, m = 3, Storage = U, D50 = 5, UNFCS = 10
      51.0      50.0       0.0       0.0       0.0       0.0       0.0       0.0
       1.0       1.0       0.0       0.0       0.0       0.0       0.0       0.0
       0.0      48.0       0.0       0.0       0.0       0.0       0.0       0.0
    6358.0    4689.0    3256.0    2084.0    1172.0     521.0     130.0       0.0
      51.0      43.8      36.5      29.2      21.9      14.6       7.3       0.0
       0.0       1.0     400.0       0.0       0.0       0.0       0.0       0.0
      50.0    1000.0    1200.0       0.0       0.0       0.0       0.0       0.0
      0.03      0.03      0.03       0.0       0.0       0.0       0.0       0.0
       3.0       3.0       0.0       0.0       0.0       0.0       0.0
       0.0       0.0       0.0       0.0       0.0       0.0       0.0
       5.0       0.3     110.0       0.0      32.0     250.0      10.0
       2.0       0.1    2195.0      11.0       0.0       0.0       0.0       0.0
      0.05     0.001       0.1      48.0       0.0       1.0       0.0
       0.0       0.0       0.0       0.0       0.0       0.0       0.0       0.0
       0.0       0.0       0.0       0.0       0.0       0.0       0.0       0.0
```

Table D.7. NWSB output file for synthetic base case; h_d = 50 ft, Storage *UP*, shape m = 3, D_{50} = 5mm.

```
H = 50, m = 3, Storage = U, D50 = 6, UNFCS = 10

  HI=     51.00  HU=     50.00  HL=       .00  HPI=       .00  HSP=      .00  PI=    .0  CA= .000  CB= .00

          (QIN(I),I=1,8)
      1.00      1.00       .00       .00       .00       .00       .00       .00

          (TIN(I),I=1,8)
       .00     48.00       .00       .00       .00       .00       .00       .00

          (RSA(I),I=1,8)
   6358.00   4689.00   3256.00   2084.00   1172.00    521.00    130.00       .00

          (HSA(I),I=1,8)
     51.00     43.80     36.50     29.20     21.90     14.60      7.30       .00

          (HSTW(I),I=1,8)
       .00      1.00    400.00       .00       .00       .00       .00       .00

          (BSTW(I),I=1,8)
     50.00   1000.00   1200.00       .00       .00       .00       .00       .00

          (CMTW(I),I=1,8)
       .03       .03       .03       .00       .00       .00       .00       .00

  ZU=  3.00  ZD=  3.00  ZC=   .00  GL=   .00  GS=   .00  VMP=   .00  SEDCON=   .00

  D50C=   .00  PORC=   .00  UWC=   .00  CNC= .0000  AFRC=   .00  COHC=    .0  UNFCC=   .00

  D50S=  5.00  PORS=   .30  UWS=110.00  CNS= .0000  AFRS= 32.00  COHS= 250.0  UNFCS= 10.00

  BR=  2.00  WC=    .1  CRL= 2195.0  SM= 11.00  D50DF=   .00  UNFCDF=   .00   BMX= 2076.   BTMX= 2195.

  DTH=  .020  DBG=  .001   H=   .1000   TEH=   48.0  ERR=   .50  FPT=   1.0  TPR=    .0

  AFRA=    .0   TH1= 61.00   H1= 16.40   TH2= 46.50   H2= 53.78   TH3= 39.25   H3=175.57   SEDCON=   .50

1
```

I	T	DTH	KG	KC	QTOT	QTS	QB	SUB	BT	HY	HC	BO	PPP	HP	TWD	DH	DHH	KIT	AGL
1	.020	.0200	1	0	6795.	6795.	4.	1.000	1.3	51.0	50.0	1.3	.6	2.0	.00	.54	.54	4	.0
2	.022	.0020	2	0	6786.	6782.	4.	1.000	1.3	51.0	49.9	1.3	158.4	.1	2.25	.11	.11	3	.0
3	.024	.0022	2	0	6785.	6780.	5.	1.000	1.3	51.0	49.8	1.3	158.8	.2	2.25	.13	.13	2	.0
4	.027	.0024	2	0	6784.	6778.	6.	1.000	1.3	51.0	49.6	1.3	159.2	.4	2.25	.15	.15	2	.0
5	.029	.0027	2	0	6783.	6775.	7.	1.000	1.3	51.0	49.5	1.3	159.7	.5	2.25	.17	.17	2	.0
6	.032	.0029	2	0	6782.	6773.	9.	1.000	1.3	51.0	49.3	1.3	160.3	.7	2.25	.20	.20	1	.0
7	.035	.0032	2	0	6780.	6770.	10.	1.000	1.3	51.0	49.1	1.3	160.9	.9	2.25	.23	.23	1	.0
8	.039	.0035	2	0	6782.	6766.	17.	1.000	1.7	51.0	48.8	1.7	161.8	1.2	2.25	.31	.31	3	.0
9	.043	.0039	2	0	6790.	6761.	29.	1.000	2.2	51.0	48.3	2.2	163.0	1.7	2.25	.44	.45	3	.0
10	.047	.0043	2	0	6810.	6754.	55.	1.000	3.1	51.0	47.7	3.1	164.9	2.3	2.25	.67	.67	4	.0
11	.051	.0043	2	0	6857.	6747.	110.	1.000	4.3	51.0	46.8	4.3	167.5	3.2	2.25	.94	.94	4	.0
12	.056	.0043	2	0	6967.	6738.	229.	1.000	6.0	51.0	45.5	6.0	171.3	4.5	2.25	1.33	1.33	4	.0
13	.060	.0043	2	0	7225.	6726.	498.	1.000	8.4	51.0	43.7	8.4	176.6	6.3	2.25	1.90	1.91	4	.0
14	.064	.0039	2	0	7731.	6713.	1018.	1.000	11.5	51.0	41.4	11.5	183.2	8.6	2.25	2.36	2.37	3	.0
15	.067	.0035	2	0	8637.	6698.	1939.	1.000	15.1	51.0	38.7	15.1	191.0	11.3	2.75	2.78	2.79	3	.0
16	.071	.0032	2	0	10107.	6682.	3426.	1.000	19.1	51.0	35.7	19.1	199.8	14.3	2.75	3.12	3.12	2	.0
17	.072	.0016	2	0	11552.	6666.	4886.	1.000	23.2	51.0	34.0	23.2	204.9	16.0	2.75	1.80	1.79	4	.0
18	.074	.0015	2	0	12419.	6662.	5757.	1.000	23.8	51.0	32.3	23.8	209.6	17.7	3.25	1.69	1.69	3	.0
19	.075	.0013	2	0	13721.	6653.	7068.	1.000	25.9	51.0	30.8	25.9	214.2	19.2	3.25	1.63	1.64	3	.0
20	.076	.0012	2	0	15155.	6645.	8510.	1.000	27.9	51.0	29.2	27.9	218.6	20.8	3.25	1.57	1.57	4	.0

KSLUMP= 1 HCK= 17.33 DELT= .00 DEL= 29.00

I	T	DTH	KG	KC	QTOT	QTS	QB	SUB	BT	HY	HC	BO	PPP	HP	TWD	DH	DHH	KIT	AGL
21	.077	.0011	2	0	18376.	6566.	11810.	1.000	52.9	51.0	29.2	29.9	218.6	20.8	3.75	.00	.00	0	29.0
22	.078	.0011	2	0	18373.	6563.	11810.	1.000	52.9	51.0	29.2	29.9	218.6	20.8	3.75	.00	.00	0	29.0
23	.079	.0001	2	0	18466.	6562.	11904.	1.000	53.0	51.0	29.1	29.9	218.9	20.9	3.75	.10	.10	2	29.0
24	.079	.0001	2	0	18570.	6561.	12009.	1.000	53.2	51.0	29.0	29.9	219.2	21.0	3.75	.11	.11	1	29.0
25	.079	.0001	2	0	18686.	6561.	12125.	1.000	53.3	51.0	28.9	29.9	219.5	21.1	4.25	.13	.13	1	29.0
26	.079	.0001	2	0	18814.	6560.	12254.	1.000	53.5	51.0	28.7	29.9	219.9	21.3	4.25	.14	.14	2	29.0
27	.079	.0001	2	0	18957.	6559.	12398.	1.000	53.6	51.0	28.6	29.9	220.4	21.4	4.25	.15	.15	1	29.0
28	.080	.0001	2	0	19115.	6558.	12556.	1.000	53.8	51.0	28.4	29.9	220.8	21.6	4.25	.17	.17	1	29.0
29	.080	.0001	2	0	19291.	6558.	12733.	1.000	54.0	51.0	28.3	29.9	221.4	21.7	4.25	.19	.19	2	29.0
30	.080	.0001	2	0	19486.	6557.	12930.	1.000	54.2	51.0	28.1	29.9	221.9	21.9	4.25	.21	.21	2	29.0
31	.080	.0001	2	0	19703.	6556.	13148.	1.000	54.5	51.0	27.8	29.9	222.6	22.2	4.25	.23	.23	1	29.0
32	.080	.0001	2	0	19946.	6554.	13392.	1.000	54.8	51.0	27.6	29.9	223.3	22.4	4.25	.25	.25	2	29.0
33	.080	.0001	2	0	20217.	6553.	13664.	1.000	55.1	51.0	27.3	29.9	224.1	22.7	4.25	.28	.28	2	29.0
34	.080	.0002	2	0	20519.	6552.	13967.	1.000	55.4	51.0	27.0	29.9	224.9	23.0	4.25	.31	.31	1	29.0
35	.080	.0002	2	0	20855.	6550.	14305.	1.000	55.8	51.0	26.7	29.9	225.9	23.3	4.25	.34	.34	1	29.0
36	.081	.0002	2	0	21236.	6549.	14687.	1.000	56.2	51.0	26.3	29.9	226.9	23.7	4.25	.38	.38	2	29.0
37	.081	.0002	2	0	21660.	6547.	15113.	1.000	56.6	51.0	25.9	29.9	228.1	24.1	4.25	.42	.42	1	29.0
38	.081	.0002	2	0	22138.	6544.	15594.	1.000	57.1	51.0	25.5	29.9	229.4	24.5	4.25	.46	.46	2	29.0
39	.081	.0003	2	0	22675.	6542.	16133.	1.000	57.7	51.0	25.0	29.9	230.8	25.0	4.25	.51	.51	1	29.0
40	.082	.0003	2	0	23221.	6540.	16681.	1.000	58.2	51.0	24.5	29.9	232.3	25.5	4.25	.51	.51	0	29.0
41	.082	.0003	2	0	23784.	6537.	17246.	1.000	58.8	51.0	24.0	29.9	233.7	26.0	4.75	.52	.52	1	29.0
42	.082	.0003	2	0	24356.	6535.	17821.	1.000	59.3	51.0	23.4	29.9	235.2	26.6	4.75	.52	.52	0	29.0

I	T	DTH	KG	KC	QTOT	QTS	QB	SUB	BT	HY	HC	BO	PPP	HP	TWD	DH	DHH	KIT	AGL
43	.082	.0003	2	0	24945.	6532.	18413.	1.000	59.9	51.0	22.9	29.9	236.6	27.1	4.75	.52	.52	1	29.0
44	.083	.0003	2	0	25544.	6530.	19014.	1.000	60.5	51.0	22.4	29.9	238.1	27.6	4.75	.52	.52	0	29.0
45	.083	.0003	2	0	26160.	6527.	19633.	1.000	61.0	51.0	21.9	29.9	239.6	28.1	4.75	.53	.53	1	29.0
46	.083	.0003	2	0	26787.	6524.	20263.	1.000	61.6	51.0	21.4	29.9	241.1	28.6	4.75	.53	.53	0	29.0
47	.083	.0003	2	0	27429.	6522.	20907.	1.000	62.2	51.0	20.9	29.9	242.6	29.1	4.75	.53	.54	1	29.0
48	.084	.0003	2	0	28082.	6519.	21563.	1.000	62.8	51.0	20.3	29.9	244.1	29.7	4.75	.53	.53	0	29.0
49	.084	.0003	2	0	28751.	6516.	22235.	1.000	63.4	51.0	19.8	29.9	245.6	30.2	5.25	.54	.54	1	29.0
50	.084	.0003	2	0	29431.	6514.	22917.	1.000	64.0	51.0	19.3	29.9	247.1	30.7	5.25	.54	.54	0	29.0
51	.084	.0003	2	0	30128.	6511.	23617.	1.000	64.5	51.0	18.8	29.9	248.6	31.2	5.25	.54	.55	1	29.0
52	.085	.0003	2	0	30838.	6508.	24329.	1.000	65.1	51.0	18.2	29.9	250.2	31.8	5.25	.55	.55	3	29.0
53	.085	.0003	2	0	31559.	6505.	25053.	1.000	65.7	51.0	17.7	29.9	251.7	32.3	5.25	.55	.54	0	29.0
54	.085	.0003	2	0	32297.	6503.	25794.	1.000	66.3	51.0	17.1	29.9	253.2	32.9	5.25	.55	.55	1	29.0
55	.085	.0003	2	0	33046.	6500.	26547.	1.000	66.9	51.0	16.6	29.9	254.8	33.4	5.25	.55	.55	5	29.0
56	.086	.0003	2	0	33807.	6497.	27311.	1.000	67.5	51.0	16.1	29.9	256.3	33.9	5.25	.55	.55	0	29.0
57	.086	.0003	2	0	34584.	6494.	28090.	1.000	68.1	51.0	15.5	29.9	257.9	34.5	5.75	.55	.56	1	29.0
58	.086	.0003	2	0	35373.	6491.	28882.	1.000	68.7	51.0	15.0	29.9	259.4	35.0	5.75	.55	.55	0	29.0
59	.086	.0003	2	0	36177.	6488.	29689.	1.000	69.3	51.0	14.4	29.9	261.0	35.6	5.75	.56	.56	1	29.0
60	.087	.0003	2	0	36993.	6485.	30508.	1.000	69.9	51.0	13.9	29.9	262.5	36.1	5.75	.56	.56	5	29.0
61	.087	.0003	2	0	37823.	6482.	31341.	1.000	70.6	51.0	13.3	29.9	264.1	36.7	5.75	.56	.56	5	29.0
62	.087	.0003	2	0	38665.	6479.	32186.	1.000	71.2	51.0	12.8	29.9	265.7	37.2	5.75	.56	.56	0	29.0
63	.087	.0003	2	0	39524.	6476.	33048.	1.000	71.8	51.0	12.2	29.9	267.3	37.8	5.75	.56	.56	1	29.0
64	.088	.0003	2	0	40393.	6473.	33921.	1.000	72.4	51.0	11.7	29.9	268.8	38.3	6.25	.56	.56	5	29.0
65	.088	.0003	2	0	41275.	6469.	34806.	1.000	73.0	51.0	11.1	29.9	270.4	38.9	6.25	.56	.56	0	29.0
66	.088	.0003	2	0	42174.	6466.	35708.	1.000	73.6	51.0	10.6	29.9	272.0	39.4	6.25	.56	.56	1	29.0
67	.088	.0003	2	0	43084.	6463.	36621.	1.000	74.2	51.0	10.0	29.9	273.6	40.0	6.25	.56	.57	5	29.0
68	.089	.0003	2	0	44005.	6460.	37545.	1.000	74.8	51.0	9.5	29.9	275.1	40.5	6.25	.56	.57	5	29.0
69	.089	.0003	2	0	44938.	6456.	38482.	1.000	75.4	51.0	8.9	29.9	276.7	41.1	6.25	.56	.57	5	29.0
70	.089	.0003	2	0	45884.	6453.	39431.	1.000	76.1	51.0	8.4	29.9	278.3	41.6	6.25	.56	.57	5	29.0
71	.089	.0003	2	0	46841.	6450.	40392.	1.000	76.7	51.0	7.8	29.9	279.9	42.2	6.75	.56	.57	5	29.0
72	.090	.0003	2	0	47812.	6446.	41366.	1.000	77.3	51.0	7.3	29.9	281.4	42.7	6.75	.56	.57	5	29.0
73	.090	.0003	2	0	48812.	6443.	42369.	1.000	77.9	51.0	6.7	29.9	283.1	43.3	6.75	.57	.56	6	29.0
74	.090	.0000	2	0	48860.	6442.	42418.	1.000	77.9	51.0	6.7	29.9	283.1	43.3	6.75	.03	.03	2	29.0
75	.090	.0000	2	0	48914.	6442.	42472.	1.000	78.0	51.0	6.6	29.9	283.2	43.4	6.75	.03	.03	1	29.0
76	.090	.0000	2	0	48973.	6442.	42531.	1.000	78.0	51.0	6.6	29.9	283.3	43.4	6.75	.03	.03	1	29.0
77	.090	.0000	2	0	49037.	6441.	42596.	1.000	78.1	51.0	6.6	29.9	283.4	43.4	6.75	.04	.04	1	29.0
78	.090	.0000	2	0	49107.	6441.	42666.	1.000	78.1	51.0	6.5	29.9	283.5	43.5	6.75	.04	.04	1	29.0
79	.090	.0000	2	0	49184.	6441.	42743.	1.000	78.1	51.0	6.5	29.9	283.6	43.5	6.75	.04	.04	1	29.0
80	.090	.0000	2	0	49267.	6441.	42827.	1.000	78.2	51.0	6.4	29.9	283.8	43.6	6.75	.05	.05	1	29.0
81	.090	.0000	2	0	49358.	6440.	42918.	1.000	78.2	51.0	6.4	29.9	283.9	43.6	6.75	.05	.05	1	29.0
82	.090	.0000	2	0	49457.	6440.	43017.	1.000	78.3	51.0	6.3	29.9	284.1	43.7	6.75	.06	.06	1	29.0
83	.090	.0000	2	0	49564.	6440.	43125.	1.000	78.4	51.0	6.3	29.9	284.2	43.7	6.75	.06	.06	1	29.0
84	.090	.0000	2	0	49681.	6439.	43241.	1.000	78.4	51.0	6.2	29.9	284.4	43.8	6.75	.07	.07	1	29.0
85	.090	.0000	2	0	49807.	6439.	43368.	1.000	78.5	51.0	6.1	29.9	284.6	43.9	6.75	.07	.07	1	29.0
86	.090	.0000	2	0	49943.	6438.	43505.	1.000	78.6	51.0	6.1	29.9	284.8	43.9	6.75	.08	.08	1	29.0
87	.090	.0000	2	0	50090.	6438.	43653.	1.000	78.7	51.0	6.0	29.9	285.1	44.0	6.75	.08	.08	1	29.0

I	T	DTH	KG	KC	QTOT	QTS	QB	SUB	BT	HY	HC	BO	PPP	HP	TWD	DH	DHH	KIT	AGL
88	.091	.0000	2	0	50250.	6437.	43813.	1.000	78.8	51.0	5.9	29.9	285.3	44.1	6.75	.09	.09	1	29.0
89	.091	.0001	2	0	50421.	6436.	43984.	1.000	78.9	51.0	5.8	29.9	285.6	44.2	6.75	.10	.10	1	29.0
90	.091	.0001	2	0	50604.	6436.	44169.	1.000	79.0	51.0	5.7	29.9	285.9	44.3	6.75	.10	.10	1	29.0
91	.091	.0001	2	0	50802.	6435.	44367.	1.000	79.1	51.0	5.6	29.9	286.2	44.4	6.75	.11	.11	1	29.0
92	.091	.0001	2	0	51012.	6434.	44578.	1.000	79.3	51.0	5.5	29.9	286.5	44.5	6.75	.12	.12	1	29.0
93	.091	.0001	2	0	51237.	6433.	44804.	1.000	79.4	51.0	5.4	29.9	286.9	44.6	6.75	.12	.12	1	29.0
94	.091	.0001	2	0	51476.	6432.	45044.	1.000	79.5	51.0	5.2	29.9	287.2	44.8	6.75	.13	.13	1	29.0
95	.091	.0001	2	0	51729.	6431.	45298.	1.000	79.7	51.0	5.1	29.9	287.6	44.9	6.75	.14	.14	1	29.0
96	.091	.0001	2	0	51997.	6430.	45567.	1.000	79.8	51.0	4.9	29.9	288.0	45.1	7.25	.15	.15	1	29.0
97	.091	.0001	2	0	52279.	6429.	45850.	1.000	80.0	51.0	4.8	29.9	288.5	45.2	7.25	.15	.15	1	29.0
98	.091	.0001	2	0	52575.	6428.	46148.	1.000	80.2	51.0	4.6	29.9	288.9	45.4	7.25	.16	.16	1	29.0
99	.092	.0001	2	0	52885.	6426.	46458.	1.000	80.4	51.0	4.5	29.9	289.4	45.5	7.25	.17	.17	1	29.0
100	.092	.0002	2	0	53207.	6425.	46782.	1.000	80.6	51.0	4.3	29.9	289.9	45.7	7.25	.17	.17	1	29.0
101	.092	.0002	2	0	53541.	6423.	47118.	1.000	80.8	51.0	4.1	29.9	290.4	45.9	7.25	.18	.18	1	29.0
102	.092	.0002	2	0	53885.	6421.	47464.	1.000	81.0	51.0	3.9	29.9	290.9	46.1	7.25	.18	.18	1	29.0
103	.092	.0002	2	0	54239.	6419.	47819.	1.000	81.2	51.0	3.8	29.9	291.4	46.2	7.25	.19	.19	1	29.0
104	.092	.0002	2	0	54599.	6417.	48182.	1.000	81.4	51.0	3.6	29.9	292.0	46.4	7.25	.19	.19	1	29.0
105	.093	.0002	2	0	54965.	6415.	48550.	1.000	81.6	51.0	3.4	29.9	292.5	46.6	7.25	.19	.19	1	29.0
106	.093	.0003	2	0	55335.	6412.	48922.	1.000	81.8	51.0	3.2	29.9	293.1	46.8	7.25	.20	.20	1	29.0
107	.093	.0003	2	0	55706.	6410.	49296.	1.000	82.0	51.0	3.0	29.9	293.6	47.0	7.25	.20	.20	0	29.0
108	.094	.0003	2	0	56077.	6407.	49670.	1.000	82.2	51.0	2.8	29.9	294.2	47.2	7.25	.19	.19	1	29.0
109	.094	.0004	2	0	56444.	6404.	50040.	1.000	82.4	51.0	2.6	29.9	294.7	47.4	7.25	.19	.19	1	29.0
110	.094	.0004	2	0	56806.	6401.	50406.	1.000	82.6	51.0	2.4	29.9	295.2	47.6	7.25	.19	.19	1	29.0
111	.095	.0004	2	0	57161.	6397.	50764.	1.000	82.9	51.0	2.2	29.9	295.7	47.8	7.25	.18	.18	1	29.0
112	.095	.0005	2	0	57506.	6393.	51113.	1.000	83.0	51.0	2.1	29.9	296.2	47.9	7.25	.18	.18	1	29.0
113	.096	.0005	2	0	57840.	6389.	51451.	1.000	83.2	51.0	1.9	29.9	296.7	48.1	7.25	.17	.17	1	29.0
114	.096	.0006	2	0	58163.	6385.	51778.	1.000	83.4	51.0	1.7	29.9	297.2	48.3	7.25	.17	.17	2	29.0
115	.097	.0006	2	0	58471.	6380.	52091.	1.000	83.6	51.0	1.6	29.9	297.6	48.4	7.25	.16	.16	2	29.0
116	.098	.0007	2	0	58762.	6374.	52388.	1.000	83.8	51.0	1.4	29.9	298.1	48.6	7.75	.15	.15	2	29.0
117	.098	.0008	2	0	59037.	6368.	52669.	1.000	83.9	51.0	1.3	29.9	298.5	48.7	7.75	.14	.14	2	29.0
118	.099	.0008	2	0	59295.	6362.	52933.	1.000	84.1	51.0	1.1	29.9	298.8	48.9	7.75	.13	.13	2	29.0
119	.100	.0009	2	0	59534.	6355.	53179.	1.000	84.2	51.0	1.0	29.9	299.2	49.0	7.75	.12	.12	2	29.0
120	.101	.0010	2	0	59755.	6347.	53408.	1.000	84.3	51.0	.9	29.9	299.5	49.1	7.75	.11	.11	2	29.0

I	T	DTH	KG	KC	QTOT	QTS	QB	SUB	BT	HY	HC	BO	PPP	HP	TWD	DH	DHH	KIT	AGL
121	.102	.0011	2	0	59958.	6339.	53619.	1.000	84.4	51.0	.8	29.9	299.8	49.2	7.75	.11	.11	2	29.0
122	.104	.0012	2	0	60142.	6330.	53813.	1.000	84.5	51.0	.7	29.9	300.1	49.3	7.75	.10	.10	2	29.0
123	.105	.0013	2	0	60309.	6320.	53989.	1.000	84.6	51.0	.6	29.9	300.3	49.4	7.75	.09	.09	2	29.0
124	.106	.0015	2	0	60459.	6309.	54150.	1.000	84.7	51.0	.5	29.9	300.6	49.5	7.75	.08	.08	2	29.0
125	.108	.0016	2	0	60591.	6296.	54294.	1.000	84.8	51.0	.5	29.9	300.8	49.5	7.75	.07	.07	3	29.0
126	.110	.0018	2	0	60708.	6283.	54424.	1.000	84.9	51.0	.4	29.9	300.9	49.6	7.75	.07	.07	3	29.0
127	.112	.0020	2	0	60809.	6269.	54541.	1.000	84.9	51.0	.4	29.9	301.1	49.6	7.75	.06	.06	3	29.0
128	.114	.0022	2	0	60897.	6253.	54644.	1.000	85.0	51.0	.3	29.9	301.3	49.7	7.75	.05	.05	3	29.0
129	.116	.0024	2	0	60971.	6235.	54736.	1.000	85.1	51.0	.3	29.9	301.4	49.7	7.75	.05	.05	3	29.0
130	.119	.0026	2	0	61033.	6216.	54817.	1.000	85.1	51.0	.2	29.9	301.5	49.8	7.75	.04	.04	3	29.0
131	.122	.0029	2	0	61082.	6194.	54888.	1.000	85.1	51.0	.2	29.9	301.6	49.8	7.75	.04	.04	3	29.0
132	.125	.0032	2	0	61121.	6171.	54950.	1.000	85.2	51.0	.1	29.9	301.7	49.9	7.75	.03	.03	3	29.0

133	.128	.0035	2	0	61149.	6145.	55003.	1.000	85.2	51.0	.1	29.9	301.8	49.9	7.75	.03	.03	3	29.0
134	.132	.0038	2	0	61166.	6117.	55049.	1.000	85.2	51.0	.1	29.9	301.9	49.9	7.75	.03	.03	3	29.0
135	.137	.0042	2	0	61176.	6086.	55089.	1.000	85.3	51.0	.1	29.9	301.9	49.9	7.75	.02	.02	1	29.0
136	.141	.0047	2	0	61186.	6052.	55134.	1.000	85.3	50.9	.0	29.9	302.0	50.0	7.75	.03	.03	1	29.0
137	.146	.0051	2	0	61197.	6015.	55182.	1.000	85.3	50.9	.0	29.9	302.1	50.0	7.75	.03	.03	1	29.0
138	.152	.0056	2	0	61174.	5974.	55200.	1.000	85.3	50.9	.0	29.9	302.2	50.0	7.75	.03	.03	1	29.0
139	.158	.0062	3	0	61214.	5929.	55285.	1.000	85.4	50.9	.0	30.0	.1	34.0	7.75	.04	.04	1	29.0
140	.165	.0068	3	0	61258.	5880.	55378.	1.000	85.5	50.9	.0	30.1	.1	34.0	7.75	.04	.04	1	29.0
141	.172	.0075	3	0	61305.	5825.	55480.	1.000	85.6	50.9	.0	30.2	.1	34.0	7.75	.05	.05	1	29.0
142	.181	.0082	3	0	61358.	5766.	55592.	1.000	85.7	50.9	.0	30.3	.1	33.9	7.75	.05	.05	1	29.0
143	.190	.0091	3	0	61415.	5700.	55715.	1.000	85.9	50.9	.0	30.4	.1	33.9	7.75	.06	.06	1	29.0
144	.200	.0100	3	0	61478.	5629.	55849.	1.000	86.0	50.9	.0	30.6	.1	33.9	7.75	.06	.06	1	29.0
145	.211	.0110	3	0	61547.	5550.	55997.	1.000	86.1	50.9	.0	30.7	.1	33.9	7.75	.07	.07	1	29.0
146	.223	.0121	3	0	61622.	5464.	56158.	1.000	86.3	50.9	.0	30.9	.1	33.9	7.75	.07	.07	1	29.0
147	.236	.0133	3	0	61705.	5370.	56335.	1.000	86.5	50.9	.0	31.1	.2	33.9	7.75	.08	.08	1	29.0
148	.251	.0146	3	0	61795.	5266.	56529.	1.000	86.7	50.9	.0	31.3	.2	33.9	7.75	.09	.09	1	29.0
149	.267	.0161	3	0	61894.	5153.	56741.	1.000	86.9	50.9	.0	31.5	.2	33.9	7.75	.10	.10	1	29.0
150	.284	.0177	3	0	62002.	5029.	56973.	1.000	87.2	50.8	.0	31.7	.2	33.9	7.75	.10	.10	1	29.0
151	.304	.0194	3	0	62120.	4894.	57226.	1.000	87.4	50.8	.0	32.0	.2	33.9	7.75	.11	.11	1	29.0
152	.325	.0214	3	0	62249.	4747.	57503.	1.000	87.7	50.8	.0	32.3	.3	33.9	7.75	.13	.13	1	29.0
153	.349	.0235	3	0	62390.	4586.	57804.	1.000	88.0	50.8	.0	32.6	.3	33.9	7.75	.14	.14	1	29.0
154	.375	.0259	3	0	62544.	4410.	58134.	1.000	88.4	50.8	.0	32.9	.3	33.8	7.75	.15	.15	1	29.0
155	.403	.0285	3	0	62712.	4219.	58493.	1.000	88.7	50.7	.0	33.3	.3	33.8	7.75	.16	.16	1	29.0
156	.435	.0313	3	0	62896.	4012.	58884.	1.000	89.1	50.7	.0	33.7	.4	33.8	7.75	.18	.18	1	29.0
157	.469	.0345	3	0	63096.	3787.	59309.	1.000	89.6	50.7	.0	34.2	.4	33.8	7.75	.20	.20	1	29.0
158	.507	.0379	3	0	63315.	3544.	59771.	1.000	90.1	50.7	.0	34.7	.4	33.8	7.75	.21	.21	1	29.0
159	.549	.0417	3	0	63555.	3281.	60274.	1.000	90.6	50.6	.0	35.2	.5	33.8	7.75	.23	.23	1	29.0
160	.594	.0459	3	0	63817.	2999.	60818.	1.000	91.2	50.6	.0	35.8	.5	33.7	7.75	.25	.25	1	29.0
161	.645	.0504	3	0	64106.	2698.	61408.	1.000	91.8	50.6	.0	36.4	.6	33.7	7.75	.28	.28	1	29.0
162	.700	.0555	3	0	64423.	2376.	62046.	1.000	92.5	50.5	.0	37.1	.6	33.7	7.75	.30	.30	1	29.0
163	.761	.0610	3	0	64773.	2037.	62736.	1.000	93.3	50.5	.0	37.8	.7	33.6	7.75	.33	.33	1	29.0
164	.829	.0671	3	0	65161.	1682.	63479.	1.000	94.1	50.4	.0	38.6	.7	33.6	7.75	.35	.35	1	29.0
165	.902	.0739	3	0	65596.	1316.	64280.	1.000	94.9	50.3	.0	39.5	.8	33.6	7.75	.38	.38	1	29.0
166	.984	.0812	3	0	66087.	947.	65140.	1.000	95.9	50.3	.0	40.5	.8	33.5	8.25	.42	.42	1	29.0
167	1.073	.0894	3	0	66650.	587.	66063.	1.000	96.9	50.2	.0	41.5	.9	33.5	8.25	.45	.45	1	29.0
168	1.171	.0983	3	0	67311.	262.	67050.	1.000	98.1	50.1	.0	42.6	1.0	33.4	8.25	.49	.49	1	29.0
169	1.279	.1081	3	0	68127.	24.	68103.	1.000	99.3	50.0	.0	43.8	1.1	33.3	8.25	.53	.53	1	29.0
170	1.388	.1081	3	0	69111.	0.	69111.	1.000	100.4	49.9	.0	45.0	1.0	33.3	8.25	.52	.52	1	29.0
171	1.496	.1081	3	0	70086.	0.	70086.	1.000	101.6	49.8	.0	46.2	1.0	33.2	8.25	.51	.51	1	29.0
172	1.604	.1081	3	0	71029.	0.	71029.	1.000	102.8	49.7	.0	47.3	1.0	33.1	8.25	.50	.50	1	29.0
173	1.712	.1081	3	0	71941.	0.	71941.	1.000	103.9	49.6	.0	48.4	1.0	33.1	8.25	.49	.49	1	29.0
174	1.831	.1189	3	0	72924.	0.	72924.	1.000	105.1	49.5	.0	49.7	1.1	33.0	8.25	.53	.53	1	29.0
175	1.950	.1189	3	0	73857.	0.	73857.	1.000	106.3	49.4	.0	50.9	1.0	32.9	8.25	.52	.52	1	29.0
176	2.069	.1189	3	0	74756.	0.	74756.	1.000	107.5	49.3	.0	52.0	1.0	32.8	8.75	.52	.52	1	29.0
177	2.188	.1189	3	0	75621.	0.	75621.	1.000	108.6	49.1	.0	53.2	1.0	32.8	8.75	.51	.51	1	29.0
178	2.307	.1189	3	0	76453.	0.	76453.	1.000	109.8	49.0	.0	54.3	1.0	32.7	8.75	.50	.50	1	29.0
179	2.437	.1308	3	0	77350.	0.	77350.	1.000	111.0	48.9	.0	55.6	1.1	32.6	8.75	.54	.54	1	29.0

180	2.568	.1308	3	0	78190.	0.	78190.	1.000	112.2	48.7	.0	56.8	1.1	32.5	8.75	.53	.53	1	29.0
I	T	DTH	KG	KC	QTOT	QTS	QB	SUB	BT	HY	HC	BO	PPP	HP	TWD	DH	DHH	KIT	AGL
181	2.699	.1308	3	0	78994.	0.	78994.	1.000	113.4	48.6	.0	58.0	1.0	32.4	8.75	.52	.52	1	29.0
182	2.830	.1308	3	0	79761.	0.	79761.	1.000	114.6	48.4	.0	59.2	1.0	32.3	8.75	.51	.51	1	29.0
183	2.961	.1308	3	0	80493.	0.	80493.	1.000	115.8	48.3	.0	60.3	1.0	32.2	8.75	.51	.51	1	29.0
184	3.092	.1308	3	0	81190.	0.	81190.	1.000	116.9	48.1	.0	61.5	1.0	32.1	8.75	.50	.50	1	29.0
185	3.235	.1439	3	0	81941.	0.	81941.	1.000	118.1	48.0	.0	62.7	1.1	32.0	9.25	.54	.54	1	29.0
186	3.379	.1439	3	0	82628.	0.	82628.	1.000	119.3	47.8	.0	63.9	1.1	31.9	9.25	.53	.53	1	29.0
187	3.523	.1439	3	0	83276.	0.	83276.	1.000	120.5	47.6	.0	65.1	1.0	31.8	9.25	.52	.52	1	29.0
188	3.667	.1439	3	0	83884.	0.	83884.	1.000	121.7	47.5	.0	66.3	1.0	31.6	9.25	.51	.51	1	29.0
189	3.811	.1439	3	0	84455.	0.	84455.	1.000	122.8	47.3	.0	67.4	1.0	31.5	9.25	.50	.50	1	29.0
190	3.955	.1439	3	0	84988.	0.	84988.	1.000	124.0	47.1	.0	68.5	1.0	31.4	9.25	.49	.49	1	29.0
191	4.113	.1583	3	0	85561.	0.	85561.	1.000	125.2	46.9	.0	69.8	1.1	31.3	9.25	.54	.53	1	29.0
192	4.272	.1583	3	0	86062.	0.	86062.	1.000	126.4	46.7	.0	71.0	1.1	31.1	9.25	.53	.53	1	29.0
193	4.430	.1583	3	0	86519.	0.	86519.	1.000	127.6	46.5	.0	72.1	1.0	31.0	9.25	.52	.52	1	29.0
194	4.588	.1583	3	0	86934.	0.	86934.	1.000	128.7	46.3	.0	73.3	1.0	30.8	9.25	.51	.51	1	29.0
195	4.747	.1583	3	0	87307.	0.	87307.	1.000	129.9	46.0	.0	74.4	1.0	30.7	9.25	.50	.50	1	29.0
196	4.921	.1741	3	0	87707.	0.	87707.	1.000	131.1	45.8	.0	75.7	1.1	30.5	9.25	.54	.54	1	29.0
197	5.095	.1741	3	0	88022.	0.	88022.	1.000	132.3	45.6	.0	76.9	1.1	30.4	9.25	.53	.53	1	29.0
198	5.269	.1741	3	0	88289.	0.	88289.	1.000	133.5	45.3	.0	78.1	1.0	30.2	9.25	.52	.52	1	29.0
199	5.443	.1741	3	0	88509.	0.	88509.	1.000	134.7	45.1	.0	79.2	1.0	30.0	9.25	.51	.51	1	29.0
200	5.617	.1741	3	0	88683.	0.	88683.	1.000	135.8	44.8	.0	80.4	1.0	29.9	9.25	.50	.50	1	29.0
201	5.809	.1915	3	0	88866.	0.	88866.	1.000	137.0	44.5	.0	81.6	1.1	29.7	9.25	.54	.54	1	29.0
202	6.000	.1915	3	0	88951.	0.	88951.	1.000	138.2	44.2	.0	82.8	1.1	29.5	9.75	.53	.53	1	29.0
203	6.192	.1915	3	0	88982.	0.	88982.	1.000	139.4	43.9	.0	84.0	1.0	29.3	9.75	.51	.51	1	29.0
204	6.383	.1915	3	0	88962.	0.	88962.	1.000	140.6	43.6	.0	85.1	1.0	29.1	9.75	.50	.50	1	29.0
205	6.575	.1915	3	0	88891.	0.	88891.	1.000	141.7	43.3	.0	86.3	1.0	28.9	9.75	.49	.49	1	29.0
206	6.786	.2107	3	0	88812.	0.	88812.	1.000	142.9	43.0	.0	87.5	1.1	28.7	9.75	.53	.53	1	29.0
207	6.996	.2107	3	0	88623.	0.	88623.	1.000	144.1	42.7	.0	88.6	1.0	28.4	9.75	.52	.52	1	29.0
208	7.207	.2107	3	0	88377.	0.	88377.	1.000	145.2	42.3	.0	89.8	1.0	28.2	9.25	.51	.51	1	29.0
209	7.418	.2107	3	0	88077.	0.	88077.	1.000	146.4	42.0	.0	90.9	1.0	28.0	9.25	.49	.49	1	29.0
210	7.650	.2318	3	0	87749.	0.	87749.	1.000	147.6	41.6	.0	92.1	1.1	27.7	9.25	.53	.53	1	29.0
211	7.881	.2318	3	0	87295.	0.	87295.	1.000	148.7	41.2	.0	93.3	1.0	27.5	9.25	.51	.51	1	29.0
212	8.113	.2318	3	0	86780.	0.	86780.	1.000	149.9	40.8	.0	94.5	1.0	27.2	9.25	.50	.50	1	29.0
213	8.345	.2318	3	0	86204.	0.	86204.	1.000	151.0	40.4	.0	95.6	1.0	26.9	9.25	.49	.49	1	29.0
214	8.600	.2550	3	0	85577.	0.	85577.	1.000	152.2	39.9	.0	96.8	1.0	26.6	9.25	.52	.52	1	29.0
215	8.855	.2550	3	0	84808.	0.	84808.	1.000	153.3	39.5	.0	97.9	1.0	26.3	9.25	.50	.50	1	29.0
216	9.110	.2550	3	0	83971.	0.	83971.	1.000	154.5	39.0	.0	99.0	1.0	26.0	9.25	.49	.49	1	29.0
217	9.390	.2804	3	0	83059.	0.	83059.	1.000	155.6	38.5	.0	100.2	1.0	25.7	9.25	.52	.52	1	29.0
218	9.671	.2804	3	0	81985.	0.	81985.	1.000	156.8	38.0	.0	101.4	1.0	25.3	9.25	.50	.50	1	29.0
219	9.951	.2804	3	0	80834.	0.	80834.	1.000	157.9	37.4	.0	102.5	1.0	25.0	9.25	.48	.48	1	29.0
220	10.260	.3085	3	0	79580.	0.	79580.	1.000	159.1	36.8	.0	103.6	1.0	24.6	9.25	.51	.51	1	29.0
221	10.568	.3085	3	0	78143.	0.	78143.	1.000	160.2	36.2	.0	104.7	1.0	24.1	8.75	.49	.49	1	29.0
222	10.907	.3393	3	0	76585.	0.	76585.	1.000	161.4	35.6	.0	105.9	1.0	23.7	8.75	.51	.51	1	29.0
223	11.247	.3393	3	0	74835.	0.	74835.	1.000	162.5	34.9	.0	107.0	1.0	23.2	8.75	.49	.49	1	29.0
224	11.620	.3733	3	0	72941.	0.	72941.	1.000	163.6	34.1	.0	108.2	1.0	22.7	8.75	.51	.51	1	29.0

```
225  11.993  .3733 3 0     70832.         0.      70832. 1.000  164.7   33.3     .0 109.3      1.0   22.2     8.25  .48  .48  1 29.0
226  12.404  .4106 3 0     68549.         0.      68549. 1.000  165.9   32.4     .0 110.4      1.0   21.6     8.25  .50  .50  1 29.0
227  12.856  .4517 3 0     65918.         0.      65918. 1.000  167.0   31.5     .0 111.6      1.0   21.0     8.25  .51  .51  1 29.0
228  13.307  .4517 3 0     63008.         0.      63008. 1.000  168.1   30.4     .0 112.7       .9   20.3     8.25  .47  .47  1 29.0
229  13.804  .4968 3 0     59837.         0.      59837. 1.000  169.2   29.3     .0 113.8       .9   19.5     7.75  .47  .47  1 29.0
230  14.351  .5465 3 0     56218.         0.      56218. 1.000  170.3   28.0     .0 114.8       .9   18.7     7.75  .47  .47  1 29.0
231  14.952  .6012 3 0     52123.         0.      52123. 1.000  171.3   26.6     .0 115.9       .9   17.7     7.25  .46  .46  1 29.0
232  15.613  .6613 3 0     47486.         0.      47486. 1.000  172.3   24.9     .0 116.9       .9   16.6     7.25  .43  .44  1 29.0
233  16.340  .7274 3 0     42204.         0.      42204. 1.000  173.2   23.0     .0 117.8       .8   15.4     6.75  .40  .40  2 29.0
234  17.141  .8001 3 0     36197.         0.      36197. 1.000  174.0   20.8     .0 118.6       .7   13.9     6.25  .35  .35  2 29.0
235  18.021  .8802 3 0     29469.         0.      29469. 1.000  174.7   18.2     .0 119.3       .6   12.1     5.75  .29  .29  2 29.0
236  18.989  .9682 3 0     21689.         0.      21689. 1.000  175.1   14.9     .0 119.7       .4    9.9     5.25  .20  .20  3 29.0
237  20.054 1.0650 3 0     12704.         0.      12704. 1.000  175.4   10.5     .0 120.0       .2    7.0     4.25  .10  .11  4 29.0
        KTT= 0     I=  238     T=  21.23
                             OUTPUT SUMMARY

   QBP  MAX OUTFLOW(CFS) THRU BREACH                                    88982.
   TP   TIME(HR) AT WHICH PEAK OUTFLOW OCCURS                             6.19
   QP   MAX TOTAL OUTFLOW(CFS) OCCURRING AT TIME TP                     88982.
   TRS  DURATION(HR) OF RISING LIMB OF HYDROGRAPH                         6.19
   TB   TIME(HR) AT WHICH SIGN. RISE IN OUTFLOW STARTS                     .00
   BRD  FINAL DEPTH(FT) OF BREACH                                        50.00
   BRW  TOP WIDTH(FT) OF BREACH AT PEAK BREACH FLOW                      139.40
   HU   ELEV(FT) OF TOP OF DAM                                           50.00
   HY   FINAL ELEV(FT) OF RESERVOIR WATER SURFACE                          .80
   HC   FINAL ELEV(FT) OF BOTTOM OF BREACH                                .000
   AGL  ACUTE ANGLE THAT BREACH SIDE MAKES WITH VERTICAL AT QBP         29.000
   QO   OUTFLOW (CFS) AT T=0.0                                          3.8335
   Z    SIDE SLOPE OF BREACH (FT/FT) AT PEAK BREACH FLOW                   .55
   TFH  TIME OF FAILURE (HR) WHICH IS LINEAR EQUIVALENT OF TRS
        OBTAINED BY USING SIMPLIFIED DAM-BREAK DISCHARGE EQUATION        23.37
   TFHI TIME OF FAILURE (HR) WHICH IS LINEAR EQUIVALENT OF TRS
        OBTAINED BY INTEGRATING QB VS TIME FROM T=0 TO T=TP              10.74
   BO   BOTTOM WIDTH (FT) OF BREACH AT PEAK BREACH FLOW                  83.97
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Discharge Hydrograph

Hydrograph omitted for brevity. A plot of the predicted discharge hydrograph can be found in Figure 4.3, page 39.

Table D.8. SIMBA input file for synthetic base case; h_d = 50 ft, Storage *UP*, shape m = 3, k_d = 0.75 ft3 lb^{-1} hr^{-1}.

```
BREACH    01/01/2005
WHA
WDC
OPTIONS   00101
IHW       8
IHH       50
USL       3
DSL       3
HDM       50
CWD       .1
CEL       50
BKD       110
UDS       1000
KDI       .75
CSS       0.2
DWD       2191
NSS       0
ELE       51
HCMODEL   6
STRUCTURE A
          0         0
          5         101.8
          10        814.8
          15        2749.8
          20        6518.2
          25        12730.8
          30        21998.8
          35        34933.3
          40        52145.3
          45        74245.9
          50        101846.3
          51        108080.1
          52        114563.2
ENDTABLE
HYD
          0.02
          0         0
          20        0
ENDTABLE
```

Table D.9. SIMBA output file for synthetic base case; h_d = 50 ft, Storage *UP*, shape m = 3, k_d = 0.75 ft3 lb^{-1} hr^{-1}. Output has been reduced 0.3-hr resolution.

Time	Qin	Qout	Qb	Qd	El	HC Pos	Attack	Hh	Width	Hc
0	0	6765	0	6764.8	51	150.1	0	0	0	50
0.3	0	6507	3	6503.8	50.974	150.073	2.59	0.816	1.008	50
0.6	0	6262	3	6258.6	50.95	149.994	4.94	1.669	1.087	49.998
0.9	0	6029	3	6025.6	50.926	149.949	7.21	2.494	1.131	49.983
1.2	0	5814	3	5811.1	50.904	149.906	9.41	3.313	1.175	49.969
1.5	0	5610	3	5606.6	50.883	149.863	11.54	4.126	1.218	49.954
1.8	0	5415	3	5411.6	50.862	149.821	13.63	4.933	1.26	49.94
2.1	0	5229	4	5225.5	50.842	149.78	15.66	5.735	1.301	49.927
2.4	0	5051	4	5047.9	50.823	149.739	17.65	6.532	1.341	49.913
2.7	0	4882	4	4878.2	50.804	149.7	19.6	7.325	1.381	49.9
3	0	4720	4	4716.1	50.787	149.661	21.52	8.114	1.42	49.887
3.3	0	4565	4	4561	50.769	149.622	23.4	8.899	1.458	49.874
3.6	0	4417	4	4412.7	50.752	149.585	25.27	9.68	1.496	49.862
3.9	0	4275	4	4270.7	50.736	149.547	27.12	10.459	1.533	49.849
4.2	0	4139	4	4134.8	50.721	149.511	28.95	11.234	1.57	49.837
4.5	0	4009	4	4004.5	50.705	149.474	30.77	12.007	1.607	49.825
4.8	0	3884	4	3879.7	50.691	149.438	32.58	12.777	1.643	49.813
5.1	0	3764	4	3760	50.676	149.402	34.39	13.545	1.678	49.801
5.4	0	3649	4	3645.2	50.663	149.367	36.2	14.312	1.714	49.789
5.7	0	3539	4	3535	50.649	149.332	38.02	15.076	1.749	49.777
6	0	3434	4	3429.2	50.636	149.297	39.85	15.84	1.784	49.766
6.3	0	3332	5	3327.5	50.623	149.262	41.69	16.603	1.819	49.754
6.6	0	3234	5	3229.9	50.611	149.227	43.54	17.365	1.853	49.742
6.9	0	3141	5	3136	50.599	149.193	45.42	18.126	1.888	49.731
7.2	0	3050	5	3045.7	50.588	149.158	47.32	18.887	1.923	49.719
7.5	0	2967	5	2962.2	50.577	149.124	49.28	19.649	1.957	49.708
7.8	0	2889	5	2884	50.567	149.089	51.32	20.411	1.992	49.696
8.1	0	2814	5	2808.5	50.557	149.054	53.39	21.175	2.027	49.685
8.4	0	2741	5	2735.6	50.547	149.019	55.51	21.94	2.062	49.673
8.7	0	2671	5	2665.2	50.538	148.983	57.69	22.707	2.098	49.661
9	0	2603	5	2597.2	50.529	148.947	59.92	23.476	2.134	49.649
9.3	0	2546	16	2529.9	50.52	147.602	112.01	23.937	3.478	49.201
9.6	0	2549	88	2461.5	50.511	143.973	299.96	24.258	7.108	47.991
9.9	0	2809	420	2388.3	50.502	137.533	772.67	24.847	13.548	45.844
10.2	0	4118	1827	2290.3	50.489	126.472	1928.27	25.877	24.609	42.157
10.5	0	9414	7305	2108.9	50.466	108.032	4711.1	27.614	43.049	36.011
10.8	0	28724	27076	1647.6	50.399	78.127	9665.42	26.861	72.954	26.042
11.1	0	48996	48305	691.2	50.225	58.596	10254.61	19.569	92.005	19.532
11.4	0	49639	49606	32.9	50.03	56.897	10138.36	19.004	92.798	18.966
11.7	0	50881	50881	0	49.808	55.184	9999.75	18.433	93.597	18.395
12	0	52167	52167	0	49.578	53.458	9846.87	17.858	94.403	17.819
12.3	0	53472	53472	0	49.342	51.718	9681.39	17.278	95.215	17.239
12.6	0	54796	54796	0	49.099	49.965	9503.11	16.694	96.033	16.655
12.9	0	56139	56139	0	48.851	48.198	9311.85	16.105	96.858	16.066
13.2	0	57500	57500	0	48.597	46.418	9107.43	15.512	97.688	15.473
13.5	0	58881	58881	0	48.336	44.625	8889.69	14.915	98.525	14.875
13.8	0	60279	60279	0	48.07	42.819	8658.48	14.313	99.368	14.273
14.1	0	61696	61696	0	47.797	41.001	8413.65	13.707	100.216	13.667
14.4	0	63130	63130	0	47.517	39.169	8155.09	13.097	101.071	13.056
14.7	0	64581	64581	0	47.232	37.325	7882.66	12.483	101.932	12.442
15	0	66049	66049	0	46.939	35.468	7596.28	11.864	102.798	11.823
15.3	0	67533	67533	0	46.64	33.6	7295.85	11.242	103.67	11.2
15.6	0	69033	69033	0	46.335	31.719	6981.29	10.615	104.548	10.573
15.9	0	70549	70549	0	46.022	29.825	6652.55	9.984	105.431	9.942
16.2	0	72081	72081	0	45.703	27.92	6309.57	9.349	106.32	9.307
16.5	0	73626	73626	0	45.377	26.003	5952.32	8.711	107.215	8.668
16.8	0	75186	75186	0	45.044	24.075	5580.78	8.068	108.115	8.025
17.1	0	76530	76530	0	44.63	22.136	5179.7	7.422	109.02	7.379
17.4	0	77842	77842	0	44.198	20.189	4765.37	6.773	109.928	6.73
17.7	0	79155	79155	0	43.758	18.234	4340.47	6.121	110.841	6.078
18	0	80469	80469	0	43.311	16.271	3905.22	5.467	111.757	5.424
18.3	0	81782	81782	0	42.856	14.301	3459.83	4.811	112.676	4.767
18.6	0	83094	83094	0	42.395	12.323	3004.54	4.152	113.599	4.108
18.9	0	84404	84404	0	41.925	10.338	2539.59	3.49	114.526	3.446
19.2	0	85712	85712	0	41.449	8.346	2065.24	2.826	115.455	2.782
19.5	0	87017	87017	0	40.965	6.347	1581.74	2.16	116.388	2.116

19.8	0	88318	88318	0	40.474	4.342	1089.39	1.492	117.324	1.447
20.1	0	89591	89591	0	39.969	2.33	588.29	0.821	118.263	0.777
20.4	0	90388	90388	0	39.321	0.314	79.45	0.15	119.203	0.105
20.7	0	89215	89215	0	38.674	0	0	0	120.14	0
21	0	87693	87693	0	38.038	0	0	0	121.067	0
21.3	0	86186	86186	0	37.412	0	0	0	121.982	0
21.6	0	84694	84694	0	36.798	0	0	0	122.887	0
21.9	0	83219	83219	0	36.194	0	0	0	123.781	0
22.2	0	81760	81760	0	35.6	0	0	0	124.664	0
22.5	0	80318	80318	0	35.017	0	0	0	125.538	0
22.8	0	78273	78273	0	34.264	0	0	0	126.399	0
23.1	0	76260	76260	0	33.524	0	0	0	127.247	0
23.4	0	74298	74298	0	32.803	0	0	0	128.082	0
23.7	0	72386	72386	0	32.101	0	0	0	128.904	0
24	0	70524	70524	0	31.417	0	0	0	129.714	0
24.3	0	68711	68711	0	30.75	0	0	0	130.511	0
24.6	0	66946	66946	0	30.1	0	0	0	131.295	0
24.9	0	64539	64539	0	29.26	0	0	0	132.067	0
25.2	0	62109	62109	0	28.413	0	0	0	132.822	0
25.5	0	59785	59785	0	27.597	0	0	0	133.561	0
25.8	0	57563	57563	0	26.812	0	0	0	134.285	0
26.1	0	55439	55439	0	26.057	0	0	0	134.994	0
26.4	0	53407	53407	0	25.329	0	0	0	135.689	0
26.7	0	50900	50900	0	24.449	0	0	0	136.369	0
27	0	48083	48083	0	23.462	0	0	0	137.029	0
27.3	0	45458	45458	0	22.53	0	0	0	137.669	0
27.6	0	43009	43009	0	21.649	0	0	0	138.292	0
27.9	0	40724	40724	0	20.814	0	0	0	138.896	0
28.2	0	38585	38585	0	20.023	0	0	0	139.483	0
28.5	0	35309	35309	0	18.822	0	0	0	140.049	0
28.8	0	32351	32351	0	17.71	0	0	0	140.59	0
29.1	0	29706	29706	0	16.69	0	0	0	141.107	0
29.4	0	27334	27334	0	15.752	0	0	0	141.601	0
29.7	0	24938	24938	0	14.785	0	0	0	142.075	0
30	0	21357	21357	0	13.305	0	0	0	142.519	0
30.3	0	18423	18423	0	12.034	0	0	0	142.929	0
30.6	0	15998	15998	0	10.934	0	0	0	143.309	0
30.9	0	13891	13891	0	9.936	0	0	0	143.663	0
31.2	0	9865	9865	0	7.897	0	0	0	143.974	0
31.5	0	7252	7252	0	6.425	0	0	0	144.234	0
31.8	0	5483	5483	0	5.326	0	0	0	144.454	0
32.1	0	1861	1861	0	2.589	0	0	0	144.618	0
32.4	0	626	626	0	1.252	0	0	0	144.685	0

SUMMARY:
OTBegins 0.000
HCAdv 0.240
TauSwitch 0.000
Breach St 0.560
HCDown 10.940
BrEnd 20.460

VITA

Ronald Dwain Tejral

Candidate for the Degree of

Master of Science

Thesis: EVALUATION OF TWO DAM BREACH MODELS AND IMPACT OF DAM AND RESERVOIR PARAMETERS ON PEAK BREACH DISCHARGE

Major Field: Biological Systems and Agricultural Engineering

Biographical:

Education: Graduated from Tri County High School, DeWitt, Nebraska, May 1990; Congress-Bundestag youth exchange, Niebüll, Germany, June, 1990-June, 1991; Attended Saint Charles Borromeo Seminary, Overbrook, Wynnewood, Pennsylvania, 1994-95; Received Bachelor of Science, Agricultural Engineering, University of Nebraska, August 15, 1998; Completed the requirements for the Master of Science in Biological Systems and Agricultural Engineering at Oklahoma State University, Stillwater, Oklahoma, May, 2009.

Experience: Research assistant, University of Nebraska, Biological Systems Engineering, September, 1992-May, 1994, May 1995-December, 1998; Research engineer, Oklahoma State University, Biosystems and Agricultural Engineering, January, 1999-May, 2002; Agricultural engineer, United States Department of Agriculture (USDA), Natural Resources Conservation Service, July, 2002-May, 2005; Agricultural engineer, USDA, Agricultural Research Service, since June, 2005

Professional Memberships: American Society of Agricultural and Biological Engineers; Association of State Dam Safety Officials

Name: Ronald Dwain Tejral Date of Degree: December, 2008

Institution: Oklahoma State University Location: Stillwater, Oklahoma

Title of Study: IMPACT OF DAM AND RESERVOIR PARAMETERS ON PEAK BREACH DISCHARGE PREDICTIONS FOR TWO MODELS

Pages in Study: 112 Candidate for the Degree of Master of Science

Major Field: Biosystems and Agricultural Engineering

Scope and Method of Study: Two computational models for embankment dam breach are reviewed, NWSB (National Weather Service BREACH) and SIMBA (Simplified Breach Analysis). The models' predictions of peak breach discharge, Q_p, were evaluated against two contrasting, well-documented physical breach tests and against a synthetic data set. Physical test embankments were approximately 6 ft in height with contrasting material properties. The first was highly erodible achieving peak discharge in about 0.5 hrs of overtopping, the second was erosion resistant and never breached into reservoir. The synthetic set was developed from a prediction equation and historical cases of dam failure. The synthetic set dam heights, h_d, ranged from 5 to 400 ft with variations of storage volume relative to height, reservoir shape, and material rate parameters. The material rate parameter for NWSB was median particle diameter, D_{50}; SIMBA's was erodibility, k_d.

Findings and Conclusions: While observations were more of a comparative nature for the synthesized set, the laboratory breaches provided known Q_b as a basis. NWSB proved wholly incapable of modeling the material properties of the laboratory breaches, predicting near instantaneous breach for both experiments. SIMBA was able to predict Q_p and even timing with remarkable accuracy. For the synthesized data sets, both models exhibited sensitivity to changes in height and relative storage volume. NWSB responded more to changing storage for higher dams, while altering this parameter had more effect on lower dams for SIMBA. NWSB was sensitive to changes in D_{50} only at a mid-range of dam heights; while SIMBA was sensitive to most variations in k_d, especially for smaller, less erodible dams. Discontinuities in the estimates of Q_p were noted at or near h_d = 50 ft, and can likely be attributed to height-dependent processes in both models. The slope of Q_p as plotted again h_d, closely matched that of the prediction equation: rather than a validation of the equation, it is actually a function of the height to storage relationship. While NWSB uses obtainable material properties, they were inadequate to describe cohesive behavior of the material. Erodibility, k_d, was in these cases a more appropriate material property for modeling dam breach.

ADVISER'S APPROVAL: Dr. Gregory J. Hanson