USE OF BREACH PROCESS MODELS TO ESTIMATE HEC-RAS DAM BREACH PARAMETERS

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Abstract The mapping of potential inundation resulting from a dam failure requires several elements; the hydrologic scenario, the possible dam failure modes, breach parameters that are associated with the failure modes, and the routing and mapping of the consequent discharge hydrograph. The unsteady flow routing model, HEC-RAS, is often used for the computation and display of downstream impacts resulting from hypothetical dam failures. Estimation of the breach parameters, such as width and development time, is done external to the model. This paper presents recent research into the use of several embankment erosion process models to estimate the HEC-RAS breach parameters. The process models evaluated incorporate several mechanisms for simulating breach development; including vertical erosion due to sediment transport, breach widening, side slope collapse, and head cutting. The use of such process models to provide information regarding the time-history of breach development for use in HEC-RAS is also presented.

INTRODUCTION

Simulation of the breaching of dams and/or levees at multiple locations in a river system can be accommodated within the river modeling system, HEC-RAS (HEC, 2008). HEC-RAS incorporates the interactions of the breach hydrographs from embankment failures with the ongoing flood dynamics throughout the system being modeled. Dam breach modeling is typically done within a larger study context that develops inflow hydrographs from various frequency storms, evaluates project spillway adequacy, estimates breach parameters, and performs routing and mapping of the resultant flood (HEC, 2007). The simplest case that can be used for testing the coupling of breach process models with HEC-RAS is that of a single reach bounded upstream by a dam with a reservoir described by a storage-elevation function. The next refinement that can be simulated is the same system with dynamic routing being used for flow in the reservoir. Additional locations for breaching simulation are levees where the breach mechanics may be similar to that of embankment dams; however, the location within the system and local hydraulics will differ from that of a main stem dam.

The geometric description of a dam breach must be estimated to simulate the resultant flood wave and downstream consequences. Some readily available models that can be used for performing dam breach outflow hydrograph computation and downstream routing are HEC-RAS (HEC, 2008), NWS-DAMBRK (Fread, 1988b), NWS-FLDWAV (Fread, 2000), and a few others. These models require that the potential breach characteristics be estimated outside of the model. Several “process” models are also available, or being developed, that simulate the progression of a dam breach using sediment transport or erosion equations to estimate erosion rates and soil mechanics relations to predict mass slope failures. One such process model that is discussed herein is the NWS-BREACH model (Fread, 1988a).

Breach characteristics can be estimated in several ways: (1) comparative analysis - comparing the project of interest with historical failures of dams of similar size, materials, and storage volume, (2) regression equations - relations developed from historical dam failures that correlate breach size and development time with dam and reservoir characteristics, and (3) application of physically based (process) computer models - programs that model the physical breaching process by using sediment transport/erosion equations, soil mechanics, and principles of hydraulics. All of these methods are viable techniques for estimating breach characteristics.

Reasonable values for the breach size and development time are needed to make a reliable estimate of the outflow hydrographs and resulting downstream inundation, flood travel times, water velocities, etc. Parameters that describe the breach size and rate of development have large uncertainty. Systems modeled with HEC-RAS may have several have possible embankment breaches, both at dams and levees. Proper simulation of floodwave movement through such a system requires that the breach development and outflow hydrographs be computed including local water upstream and downstream water surface elevations and then be integrated into the system model.

Dam Break Simulation with HEC-RAS Dam break simulations are performed with HEC-RAS for dam safety studies as well as for flood damage analyses for situations that involve possible levee breaches. These studies usually need to address the following situations and their associated uncertainties.

- Hydrologic Scenarios
  - Large hydrologic event (e.g., PMF)
  - Sunny day failure
- Failure Modes
  - Overtopping
  - Piping
- Failure initiation
  - Reservoir stage
  - Reservoir stage + duration
  - Selected time
- Breach description input data
  - Maximum breach bottom width
  - Ultimate breach bottom elevation
  - Breach development time
  - Failure mode and initiation specification
  - Breach growth progression – linear or nonlinear (perhaps from a process model)
  - Breach side slopes

Data Requirements for Breach Simulation with HEC-RAS The HEC-RAS simulation model uses the following parameters to describe a dam breach:

- **Location**: transverse location of the centerline of the breach in the dam
- **Failure Mode**: overtopping or piping
- **Shape and Progression**: bottom elevation, bottom width, left and right side slopes. Linear or non-linear time development.
- **Formation Time**: critical breach development time

- **Trigger Condition**: pool elevation, pool elevation + duration, or clock time
- **Weir and Pipe Flow Coefficients**: weir coefficients are used to compute overtopping/weir flow, and an orifice coefficient is used to compute piping/pressure flow.

Failure Location This is the transverse location of the breach centerline. This is selected based on many factors (type and shape of dam, failure type and mode). In general, one should consider all factors about the dam, including any historical knowledge of seepage and foundation problems, and place the breach location in the most probable location for each failure type. Commonly, the center of the breach is set to the centerline of the downstream main channel.

Failure Mode The HEC-RAS breach hydraulic computations include both overtopping and piping failure modes. Any other failure mode can be approximated with one of those two methods. The failure mode is the mechanism by which the breach occurs. Overtopping failures start at the top of the dam and grow to maximum extents; while a piping failure can start at any elevation/location and grow to the maximum extents. The ultimate breach size and breach time are much more critical in the estimation of the outflow hydrograph than the failure mode. The focus herein is on overtopping failures.

Breach Formation Time HEC-RAS requires that a breach formation time be provided. The breach formation time is described as follows (HEC, 2008): "This time represents the duration from when the breach begins to have some significant erosion, to the full development of the breach." The estimation of the breach formation time is done outside of the HEC-RAS software. It can be estimated from general guidance (USACE, 1980), empirical methods or from the results of process model applications. The use of process models should significantly decrease the uncertainty in the estimation of this parameter as a process model can be tailored to simulate a specific structure rather than using an estimate for a class of structures.

Breach Shape Definition The description of the breach shape in HEC-RAS consists of the height of the breach, breach width, and side slopes. These values represent the maximum breach size. A diagram showing this generalized breach is shown on Fig. 1.

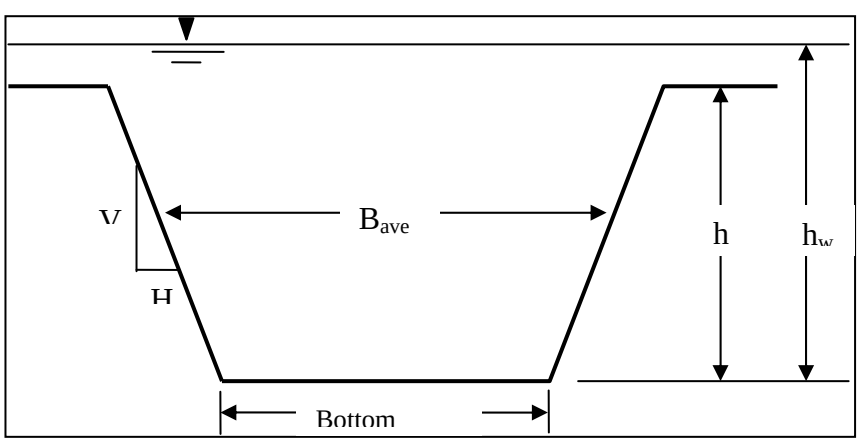

Figure 1 Definition of HEC-RAS Breach Geometric Parameters.

The breach width is described as the average breach width (B_{ave}) in several of the empirical equations. HEC-RAS uses the breach bottom width for input. The breach height (h_b) is the vertical extent from the top of the dam to the invert elevation of the breach. Many publications and equations also use the height of the water (h_w), which is the vertical extent from the maximum water surface to the invert elevation of the breach

The breach dimensions, as well as the breach formation time, must be estimated outside of HEC-RAS. Many case studies have been performed on data from historic dam failures leading to guidelines, regression equations, and computer modeling methodologies for estimation of the dam breach size and formation time. One of the most comprehensive summaries of the literature on historic dam failures is a Bureau of Reclamation report (Wahl, 1988). Although this report discusses all types of dams, it focuses on earthen embankment dams. Guidance for selection of breach parameters for concrete (arch, gravity, buttress, etc), steel, timber, and other types of structures is very sparse.

Cooperation with the CEATI Dam Breach Erosion Project (Wahl, 2009) A consortium of international dam owners is collaborating through the Dam Safety Interest Group (DSIG) of CEATI (CEATI) in evaluation of the performance of embankment breach models. Since 2004, a DSIG working group on embankment dam erosion and breach modeling has been working to facilitate the development and deployment of a physically-based embankment dam breach model. Work is being performed by DSIG-member organizations, interested non member organizations, and contractors. In addition to the in-kind contributions of the working group members, other DSIG-member organizations are sponsoring the work through cash contributions. Key working group members represent the following organizations:

- Electricité de France
- U.S. Army Corps of Engineers
- Hydro Quebec and contractor Montreal Polytechnic University
- U.S. Bureau of Reclamation
- USDA-Agricultural Research Service (ARS)
- HR Wallingford
- Ontario Power Generation
- Elforsk AB

The work reported herein is supported by, and contributes to, both the CEATI investigation and the Corps' Dam Safety program. The results shown below for the process models are preliminary and not necessarily representative of the final results of the model evaluation group (Wahl, 2009).

Previous Investigations on the Use of Empirical Methods Determining the size and growth rate for breaches is not a precise exercise. Therefore, use of simulation models such as HEC-RAS allows for quick evaluations of the impacts of a range of those parameters on the results. Indeed, in practice, the risk studies of potential failures utilize a range of breach parameters and hydrologic scenarios.

Regression Equations A number of regression equations that estimate breach parameters have been evaluated for use with HEC-RAS. The emphasis of that work (Gee and Brunner, 2007;

Gee, 2009a; Gee, 2009b) has been on interpreting and applying the results of the empirical methods for modeling overtopping failures with RAS. The following regression equations have been used for several dam safety studies:

- Froehlich (1987, 1995a, 1995b)
- MacDonald and Langridge-Monopolis (1984)
- Von Thun and Gillette (1990)

Froehlich utilized 63 earthen, zoned earthen, earthen with a core wall (i.e. clay), and rockfill data sets to develop a set of equations to estimate average breach width, side slopes, and failure time. In the application of these equations reported herein, the height of the breach is calculated by assuming that the breach goes from the top of the dam to the natural ground elevation at the centerline of the breach location.

MacDonald and Langridge-Monopolis (1984) utilized 42 data sets (predominantly earthfill, earthfill with a clay core, and rockfill) to develop a relationship for the "Breach Formation Factor." The Breach Formation Factor is a product of the volume of water released from the dam and the height of water above the dam. They then related the breach formation factor to the volume of material eroded from the dam's embankment. The resulting ultimate breach dimensions are a function of the volume eroded and the embankment geometry. The MacDonald and Langridge-Monopolis paper states that the breach should be trapezoidal with side slopes of 0.5H:1V. The breach size is computed by assuming that the breach erodes vertically to the bottom of the dam and then erodes horizontally until the maximum amount of material has been eroded or the abutments of the dam have been reached. Note that the MacDonald and Langridge-Monopolis paper states that the equation for the breach formation time is an envelope of the data from earthfill dams. An envelope equation implies that the equation will tend to give high estimates of the actual breach time (for homogenous earthfill dams).

Von Thun and Gillette (1990) used 57 dams from both the Froehlich (1987) and the MacDonald and Langridge-Monopolis (1984) papers to develop their methodology. The method suggests the use of breach side slopes of 1.0H:1.0V; except for dams with cohesive soils, where side slopes should be on the order of 0.5H:1V to 0.33H:1V. Von Thun and Gillette developed two different sets of equations for the breach development time depending upon the embankment material.

The impact of the breach parameters estimated by these methods on the computed breach outflow hydrographs has been previously documented (Gee and Brunner, 2007; Gee, 2009a and 2009b). Recent work by Xu and Zhang (2009) has proposed new regression equations for breach parameters based on an updated and expanded data set. These equations will be evaluated for use in HEC-RAS in the future.

Applications to Some Historic Overtopping Failures The various methods mentioned above have been applied to a few historic data sets selected by the CEATI evaluation group. The breach properties and the associated dam, reservoir and hydrologic information were subsequently used to replicate the situations with HEC-RAS.

Oros Dam Oros dam (Brazil) was under construction when it failed by overtopping in March of 1960 (CEATI). The dam height was about 35.5m. It was composed of a clay core with sand and

rock shoulders. The empirical methods of MacDonald, Froehlich and VonThun were applied to this structure along with the NWS-BREACH process model. The volume of water released was estimated to be $660*10^6$ m^3 (CEATI). Table 1 summarizes the resulting breach parameters computed by these methods.

Table 1 Oros Breach Parameters.

Oros	**Parameter**		
Method	W_b (m)	Side Slopes (h:v)	t_f (hrs)
MacDonald	900	0.5	3.7
Froehlich	305	1.4	4.8
VonThun	132	0.33	1
NWS-BREACH	284	0.6	7.3
SIMBA*	208	0.6	2.4
HR-BREACH*	416	0.6	2.3
Reported	**200**	**0**	**6.5 to 12**

* Preliminary values pending results of the breach model testing group.

Banqiao Dam Banqiao Dam (China) failed by overtopping from a large storm in 1975 (CEATI). The dam was constructed of a clay core containing shale. The upstream and downstream fill was homogeneous earth. It can be assumed that, due to construction methods (primarily non-mechanized), that the core was poorly compacted. The dam was about 24.5 meters high with a crest elevation at 116.34m. Crest width was 6m and length 2020m. The upstream slope was 3H:1V and downstream 2.5H:1V. The design capacity for the spillway and outlet works was 1742 m^3/sec; the estimated peak inflow was about 13,000 m^3/sec when breaching occurred. The estimated breach parameters are shown in Table 2

Table 2 Banqio Breach Parameters.

Banqiao	**Parameter**		
Method	W_b (m)	Side Slopes (h:v)	t_f (hrs)
MacDonald	1037	0.5	3.4
Froehlich	281	1.4	7
VonThun	108	0.33	0.7
NWS-BREACH	641	0.6	3.6
SIMBA*	210	0.6	6.0
HR-BREACH*	820	0.6	4.4
Reported	**210**	**0**	**1.5**

* Preliminary values pending results of the breach model testing group.

Norway Test 4 This test was from the Norwegian research project on the stability and breaching of embankment dams (HR Wallingford, 2008). Data were obtained from large scale field tests. In this case the dam was 5m high with a crest elev. of 369.84m. The crest width was 2.0m and length 39m. Slope of the upstream face was 1.9H:1V; the downstream face was 1.6H:1V. The dam was constructed with gravels of 3 to 80mm diameter having a D_{50} of 4.75mm. An overtopping failure was produced by notching the crest and then managing the inflow via releases from an upstream dam in an attempt to keep the pool elevation constant. The results of applying the various methods to estimate HEC-RAS input parameters are shown in Table 3.

Table 3 Norway4 Breach Parameters.

Norway 4	**Parameter**		
Method	W_b (m)	Side Slopes (h:v)	t_f (hrs)
MacDonald	3.5	0.5	0.14
Froelich	2.8	1.4	0.15
VonThun	13.6	1	0.35
NWS-BREACH	2.1	1.3	0.02
SIMBA*	9.8	1.3	0.22
HR-BREACH*	36	1.3	0.02
Reported	**10**	**0**	**0.08 to 0.12**

* Preliminary values pending results of the breach model testing group.

Use of Process Model Results within HEC-RAS Breach process models can be used to obtain estimates of the ultimate breach dimensions as well as the development time. These values can then be used in HEC-RAS similarly to the use of breach parameters estimated using empirical techniques. Furthermore, the process models provide information on the time history of the breach development. The breach dimensions are usually assumed to vary linearly in time as the breach progresses from initiation to maximum size. RAS provides for input of a time growth template as shown on Fig. 2 to mimic conditions where the breach may grow slowly at first then accelerate as time advances.

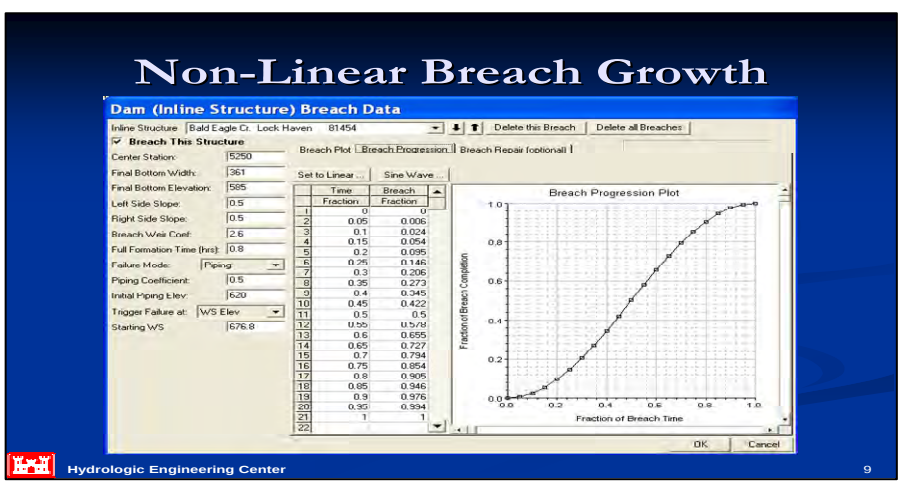

Figure 2 Non-linear Breach Development

The process models being investigated provide details regarding the temporal growth of the breach. One mechanism for coupling these models with HEC-RAS is to extract the temporal breach development from the simulations and translate that into RAS input as non-linear breach development. The following results are for NWS-BREACH. Other process models such as SIMBA (Hanson, et. al., 2005) and HR-BREACH (Mohamed, 2002) will be tested as part of the ongoing research; however results from those tests are not yet available. A brief summary of the process models that are being evaluated is given below (Wahl, et. al., 2008).

NWS-BREACH (Fread, 1988a) The NWS-BREACH model is a "process" model in that it uses soil stability mechanics and sediment transport relationships to simulate the breach development. The model uses sediment transport equations to compute the rate of erosion and size of a breach given information regarding the soil characteristics of the dam material, the inflow hydrograph, etc. Enlargement of the breach over time is computed by sediment transport equations, sudden collapse due to excess hydrostatic pressure and width expansion by slope stability. Sediment transport equations are available for either cohesive or noncohesive materials. Schematics showing the soil mechanics incorporated in this model are reproduced in Figures 3 and 4.

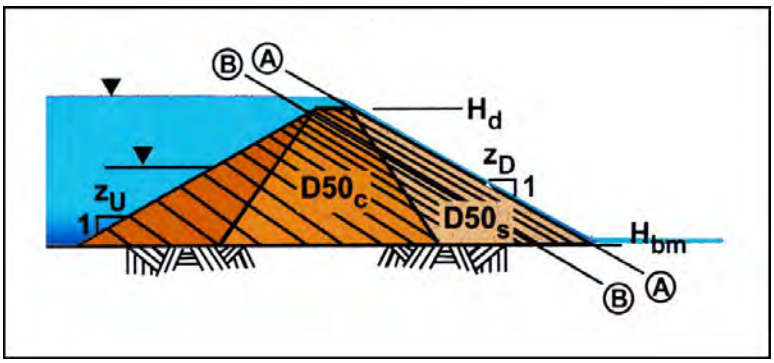

Figure 3 NWS BREACH Dam Section.

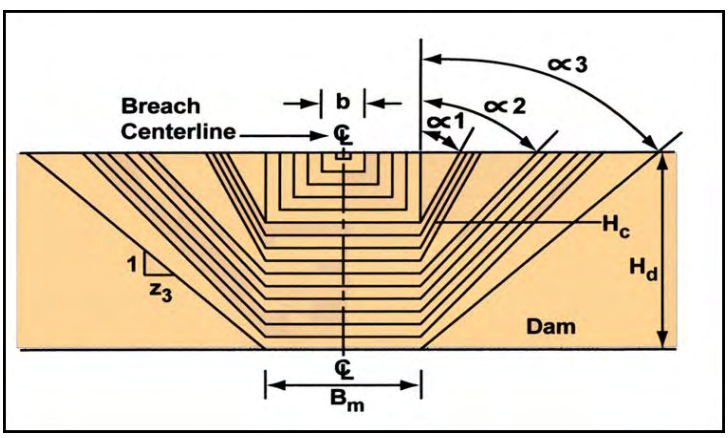

Figure 4 NWS BREACH Development Scheme.

SIMBA This model is under development at the NRCS-ARS Hydraulic Engineering Research Unit, Stillwater, Oklahoma (Hanson, et. al., 2005). SIMBA was originally developed to analyze laboratory dam breach experiments and is being incorporated into a larger suite of dam analysis

tools targeted at application to the large inventory of NRCS dams. The SIMBA breach formation algorithm includes headcut formation, deepening, lateral widening and upstream advancement.

HR-BREACH Under development at HR Wallingford, Great Britain. HR-BREACH (Mohamed, 2002) is being developed and applied for direct application to dam safety, emergency management and flood risk management needs. The erosion mechanics simulated in HR-BREACH include shear, sliding and overturning failure of soil masses.

All three of these process models make use of measured, or estimated, embankment soil characteristics such as grain size and erodibility. The use of these parameters with a hydraulic sediment transport model sets them apart from previous embankment techniques for estimating breach parameters from curve fitting to historic events (Gee and Brunner, 2007; Gee, 2009a,b).

Translation of Process Model Output to RAS Input The primary output of SIMBA and HR-BREACH are graphic displays of the erosion process, although they also create text files. The NWS-BREACH model produces only text output. The information contained in these files includes the computed breach widths and breach outflows as functions of time. As a test for using the output from a process model for preparation of HEC-RAS input, the NWS-BREACH output for breach width was non-dimensionalized for each of test data cases using the breach initiation time, time of maximum width and the initial and final breach widths. Shown on Figures

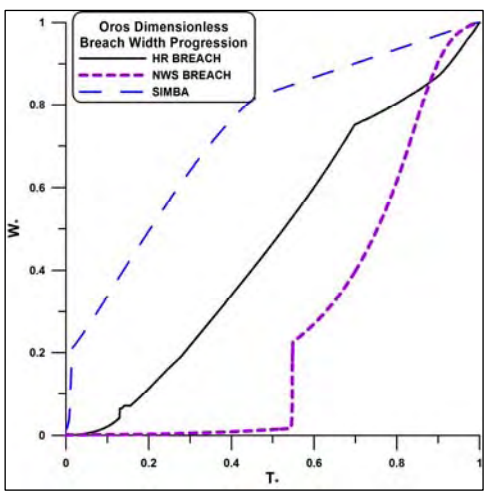

Figure 5 Oros Dam Dimensionless Breach Progression

5-7 are the resulting dimensionless breach formation curves for the test cases They are presented as dimensionless breach width (W_*) as a function of dimensionless time (T_*). This type of data representation will be useful for incorporating process model results into HEC-RAS and evaluating their performance.

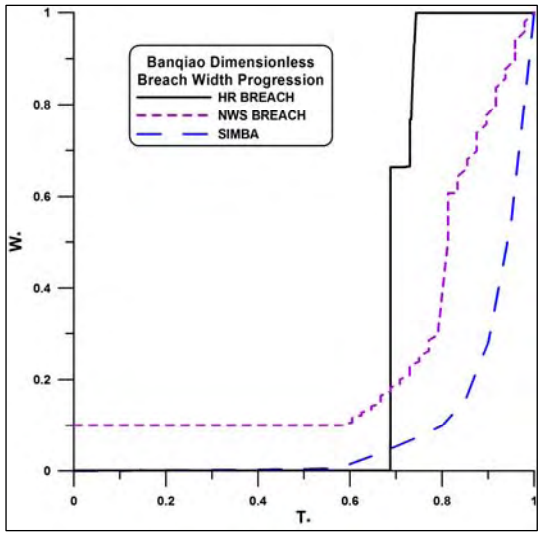

Figure 6 Banqio Dam Dimensionless Breach Progression.

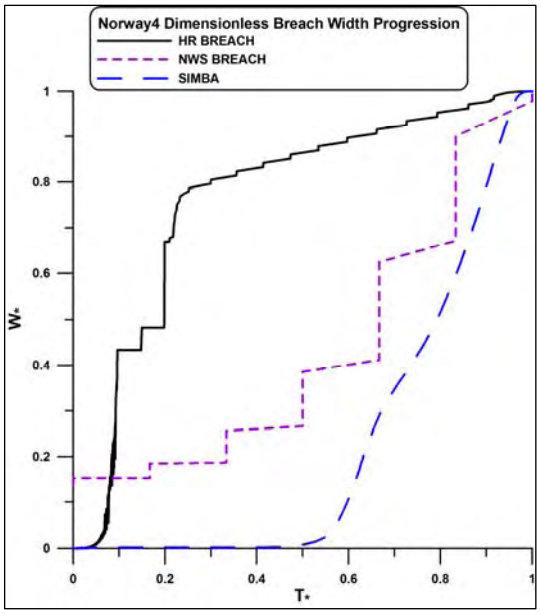

Figure 7 Norway4 Test Dimensionless Breach Progression.

Conclusions and Observations Several techniques are available for estimating the breach parameters resulting from dam overtopping and subsequent erosional failure. These techniques are predominately empirical, based on fitting relationships between key parameters such as water depth behind the dam, reservoir volume and historic observations of breach dimensions. Process models, such as NWS-BREACH, are being evaluated for use to estimate breach parameters. Techniques are being developed to interpret and utilize the breach parameters estimated by these methods in the unsteady flow routing model; HEC-RAS. The various methods predict a wide range of breach parameters and therefore, a large difference in outflow hydrographs. What is

needed for computing outflow hydrographs is the progression of the hydraulic control; be it a weir flow in the case of overtopping or an orifice flow in the case of piping. The hydraulic computations done in HEC-RAS assume that the hydraulic control progresses based on a failure time estimated from the method applied.

To address some of these issues, process models that are currently being developed and tested (Wahl, 2009) are also being evaluated for use with HEC-RAS. The expected advantage of use of this type of model is the ability to relate breach parameters to the materials and construction of the structure of interest. Tracking of the progression of the hydraulic control during breaching should be improved as well. The computed breach details from the process models need to be clarified and interpreted for use in the generalized breach simulation that RAS embodies. The time history of breach development yielded by the process models can be incorporated rather directly into HEC-RAS by use of the non-linear breach development input. Implementation of this capability was demonstrated for several tests. Future work will involve comparison of the computed and observed data using the results from controlled experiments.

Disclaimer. The views expressed in this paper are those of the author and do not necessarily reflect the policy or position of the U.S. Army Corps of Engineers.

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