COMPARING PROCESS-BASED BREACH MODELS FOR EARTHEN EMBANKMENTS SUBJECTED TO INTERNAL EROSION

Ronald D. Tejral, Agricultural Engineer, ronald.tejral@ars.usda.gov, and
Sherry L. Hunt, Research Leader and Research Civil Engineer, sherry.hunt@ars.usda.gov,
USDA Agricultural Research Service, Hydraulic Engineering Research Unit, Stillwater, OK

Abstract: A sustainable infrastructure is one for which the risks are understood. Part of understanding the risks for dams is considering the consequences of failure. Predicting the potential flooding from a dam site requires prediction of outflow resulting from breach. Conservative estimates from the assumption of instantaneous breach or from an upper envelope of historical cases are readily computed, but these estimates do not reflect the properties of a specific dam. If it is desired to understand the effects of soil materials, embankment construction, and reservoir characteristics, a process-based model is needed.

WinDAM C is the most recent module of the dam breach software under development by USDA-NRCS in cooperation with USDA-ARS and Kansas State University. It builds on the functionality of previous WinDAM releases (evaluation of embankment surface protection, breach by overtopping, and integrity of auxiliary spillways) by adding the ability to evaluate internal erosion. A process-based model of this type provides an additional tool for the engineer to evaluate the potential impact of site-specific characteristics including erosion process, embankment materials, reservoir storage, and embankment geometry. In addition, this tool may aid in the development of flood warning systems, emergency action plans, and prioritizing dams for rehabilitation.

In this study, results of WinDAM C are compared and contrasted to those obtained using BREACH. A set of hypothetical, synthetic dams was used to represent the range of USDA Small Watershed Structures by varying height and reservoir volume augmented by three variations of detachment/transport rate. Outcomes of historical failure cases and physical model studies were compared to the synthetic set. The work suggests that WinDAM is predicting in the correct order of magnitude and exhibiting appropriate sensitivity to material parameters.

INTRODUCTION

Dams are a component of infrastructure that play many critical roles: supplying municipal and rural water (i.e. for consumption, recreation, agricultural production, etc.), generating or even storing energy, and flood protection for not only populations of residents located downstream but also infrastructure like homes, utilities, and transportation routes. Take for example the subset of flood protection dams that were constructed through the assistance of the USDA Small Watershed Program. These dams were built in partnership with the USDA Natural Resources Conservation Service, formerly the Soil Conservation Service. Even in early projects, sustainability was considered. Careful consideration was given to assure cost was justified by the benefits. Furthermore, federal conservationists and private landowners laid out plans that reduced soil loss, thereby mitigating sediment delivery to the reservoir.

Another facet in the sustainability of dams is risk analysis. The essential questions revolve around 1) identifying incident types and their probabilities and 2) assessing the outcome of each incident type if it were to occur. This report is concerned with the latter, and for that purpose estimates from the assumption of instantaneous breach or from an envelope of historical cases are readily computed. However, the effect is that all dams sharing only the most basic parameters, e.g. height and storage, are predicted to behave identically. Even the limited number of failure cases illustrates this is not true. If it is desired to understand the effects of soil materials, embankment construction, and reservoir characteristics, a process-based model is needed.

Fread (1988) with the National Weather Service developed an early model (BREACH) for breach prediction. Modelers could examine breach by modes of overtopping and internal erosion, which was termed piping. Erosion was computed using the Meyer-Peter and Müller formula as adapted for steep channels by Smart (1984).

WinDAM C is the most recent module of the dam breach software under development by USDA-NRCS in cooperation with USDA-ARS and Kansas State University. Earlier modules supported evaluation of embankment surface protection, breach by overtopping, and integrity of auxiliary spillways. In contrast to BREACH, erosion is computed as detachment-limited and taking the form of a headcut. The headcut behavior is included in the modeling of breach by internal erosion.

To compare these models, a set of inputs was developed which represent the trends of the dams in the USDA Small Watershed Program. Outcomes of historical failure cases and physical model studies were compared to those for representative dams within the synthetic set. This is a part of a more comprehensive and ongoing effort to verify and validate WinDAM C.

METHODS

Because few high quality data sets exist, this exercise was conducted using a synthetic set of dams. This set is derived from existing trends in dams and physical modeling. To aid in assessing the models, other methods of peak breach discharge were used as comparators.

Synthetic Set: The synthetic set of dams consists of a realistic series of dam sizes to evaluate and compare model predictions. A comprehensive database of basic dam parameters is found in the National Inventory of Dams maintained by US Army Corps of Engineers (2007). This database was used to quantify a typical dam built under the USDA Small Watershed Program. Height was selected as the independent variable and median height was found to be 32 ft. A series of heights based on powers of two were selected to include the median and span the range within the USDA Small Watershed Program from 4 to 128 ft.

Reservoir Characteristics: The next step was to define a height to storage relationship. The median trace of maximum storage volumes through these heights with bin boundaries determined by midpoints in logarithmic space was constructed. For example, the representative reservoir storage for 32 ft dams was selected by finding median from within $2^{4.5} \leq h_d < 2^{5.5}$ ft, or $22.6 \leq h_d < 45.3$ ft. A second-degree polynomial was fit to the values:

$$V_{max} = 0.39h_d^2 - 2.5h_d + 220 \quad (1)$$

where V_{max} = maximum storage volume (assumed to correspond to top of dam), ac-ft, and
h_d = dam height, ft.

Storage relationship is plotted in Figure 1; reduced data are shown in Table 1.

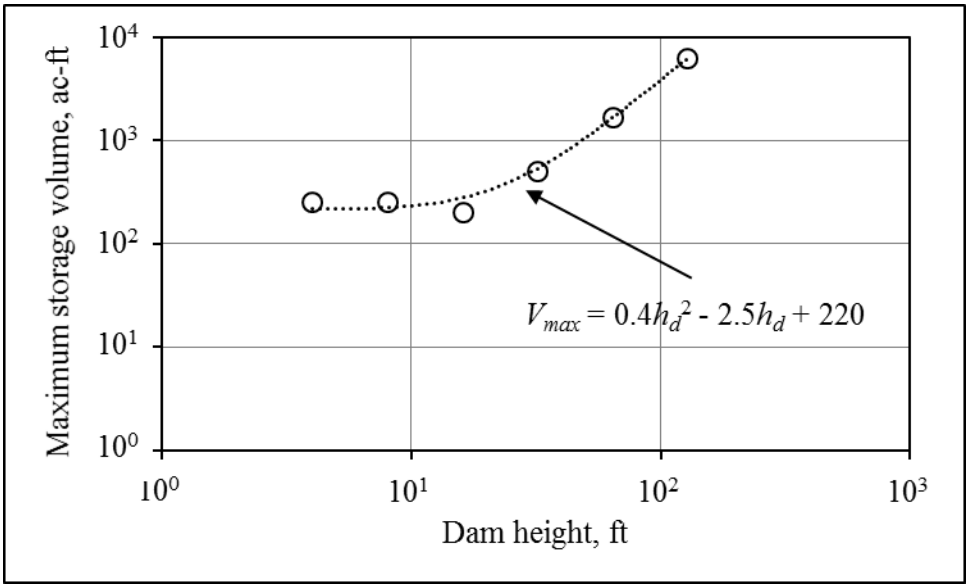

Figure 1 Dam height versus maximum storage volume.

The other reservoir characteristic is shape, which can be described by a hypsometric function. It is presented here similar to Walder and O'Connor (1997):

$$V = V_{max}\left(\frac{h}{h_d}\right)^m \quad (2)$$

Where V = volume of water in reservoir at h, ac-ft,
h = reservoir level, relative to base of dam, ft, and
m = shape parameter.

A fixed shape as defined by m = 3 was used throughout. This reservoir shape may be visualized as a cone as per Clarke (1982) or pyramid (of any base) with vertex at bottom and base defined by water surface.

While WinDAM accepts hypsometry data as height versus either volume or area, BREACH is restricted to area. Equation 2 was differentiated with respect to h to solve for area.

Dam Geometry: Embankment length is included in the NID. In finding the median length for each range of dam height, interesting behaviors are observed and reported in Table 1. Short dams (4 and 8 ft) tend to be long relative to their height. A plausible explanation are NID criteria, which would exclude all low hazard dams in this range unless they are both 6 ft high and store 50 ac-ft

or more; dams that meet inclusion on this criterion alone will tend to be long. From median heights of 16 to 64 ft, the trend is for length to increase linearly with height. This part of the data behaves as one might expect. These expectations are not unreasonable given this is the region in which bulk of data resides, and therefore has shaped our expectations. However, the trend does not continue into the bin with median height of 128 ft. Here, the explanation is likely a combination of topography and design criteria. The authors suspect that in general these dams are located in more steeply incised valleys, and were therefore taller to attain the storage necessary for flood control. This tendency toward a narrower valley led, in turn, to shorter lengths. Despite the lack of a clear trend, the overall variation in length was not extreme: median lengths do not even double (while dam height and maximum volume span one and nearly three orders of magnitude, respectively). For this reason, a single length of all dams was arrived at from average of the median lengths rounded to 1 significant figure: 900 ft.

While length was a field in the NID, other guidance was needed to select top width and slopes. A relationship for varying top width was defined using guidance on minimum top width by USDA-NRCS (2005). While actual top widths may be greater, it was assumed that these minimums were representative. The resulting top widths are reported in Table 1.

The final geometric considerations were upstream and downstream slopes. According to US Bureau of Reclamation (1987) upstream slopes are typically 2.5 or 3 (horizontal) to 1 (vertical). Similarly, Ralston (1987) stated that downstream slopes are usually 2.5:1 or 3:1. For the exercise, 3:1 was selected for both upstream and downstream slopes.

Table 1 Dam heights, medians of maximum storage volume, maximum storage volume of synthetic set, median crest lengths, and top widths.

Dam height, h_d, ft	Bin median of Maximum Storage Volume, ac-ft	Maximum Storage Volume as computed by eqn. 1, V_{max}, ac-ft	Median crest length, ft	Top Width, ft
4	254	220	1231	8
8	253	220	931	8
16	203	280	706	10
32	503	540	840	14
64	1687	1660	1018	14
128	4806	6300	855	16

Material Properties: Each model requires some quantification of the rate at which material comprising the dam will be eroded or transported. In WinDAM C, the notable parameters are erodibility (k_d) and critical shear stress (τ_c). They are obtainable by jet erosion test developed by

Hanson (1991) among other methods. The rate of headcut advance may be increased by slide of the headcut face principally as a function of undrained shear strength (c_u).

BREACH uses the Meyer-Peter and Müller equation as modified for steep slopes by Smart (1984) to model transport. This relation employs descriptors of the material's gradation: uniformity (D_{90}/D_{30}) and median particle size (D_{50}), being more sensitive to the latter. Additionally, the rate of failure can be increased by computations which rely on strength parameters, cohesion (C) and friction angle (ϕ) to predict slope failure. In contrast to WinDAM, these slope failures are of the channel sides.

Rather than arbitrarily varying any or all these parameters, three combinations of these were selected to correspond to physical tests conducted by ARS. The experiments from which they were taken presented a range of failure rates: Breach formation in less than 30 minutes to incomplete breach (initiation, but not formation) at 24 hours. Representative values of the soil test results and estimated parameters are presented in Table 2. For BREACH, gradation was available, but strength parameters were estimated from unconfined compression results.

Soils information also may be used by BREACH to estimate Manning-Strickler roughness. In an example Fread (1988) recommended use of Darcy friction factor and Moody diagram for a soil with median grain size diameter of 1 mm. As all soils represented here were of $D_{50} < 1$ mm, that was the method employed.

Table 2. Soils information.

Soil Property	Synthetic subset		
	High	Medium	Low
Unified Classification	SM	ML	CL
Plasticity Index	non	3	15
Erodibility, k_d, $ft^3\ lb^{-1}\ hr^{-1}$	70	1.3	0.3
Critical shear stress, τ_c, psf	0	0.2	0.2
Undrained shear strength, c_u, psi	300	700	1700
Cohesion, psf	150	400	1000
Friction angle, degrees	32	32	28
D_{50}, mm	0.14	0.04	0.02
Uniformity, D_{90}/D_{30}	4	50	130

Initial Conditions: Both models define the path of internal erosion very simplistically. The user specifies initial dimensions and invert elevation, and it is assumed to be horizontal and perpendicular to the crest. Longitudinally, BREACH models the path as located at center of dam relative to length, while WinDAM allows the station to be specified. For these simulations,

internal erosion was modeled as located at the centerline station and at elevation coinciding with $0.25h_d$ above base of dam base. The internal erosion was assumed to be initiated with a void square in cross section and having dimensions of 0.2 ft high and 0.2 ft wide.

A sunny-day failure is simulated with water surface elevation at $0.75h_d$ above dam base and little or no inflow. BREACH has been known not to run with a hydrograph having zero inflow as experienced by Tejral (2009), and therefore a constant inflow of 1 cfs was used.

Comparators: To provide context for the model results, USDA-NRCS peak discharge criteria and a subset of failure cases and experiments were used as comparators.

TR-60 Peak Breach Discharge: The peak breach discharge as predicted by the criteria in USDA-NRCS (2005) TR-60 was computed for each dam of the synthetic set. Because depth of water for all dams was less than 103 ft, the first equation that applied was

$$Q_{max} = (1{,}100)\left[\frac{(V_s)(H_w)}{A}\right]^{1.35} \tag{3}$$

where Q_{max} = peak discharge, ft^3/s
V_s = reservoir storage at time of failure, ac-ft
H_w = depth of water at time of failure, ft, and
A = cross-sectional area of embankment at breach location, ft^2.

Recall that short dams of the synthetic set had disproportionally large storage relative to population. This brought into play additional criteria that places an upper envelope on peak discharge (when $H_w \leq 103$ ft).

$$Q_{max} = (65){H_w}^{1.85} \tag{4}$$

The effect is that Q_{max} for the dam heights of 4 and 8 ft plot slightly above the trend established by higher dams.

TR-60 additionally considers effect of valley cross section. Here it was assumed that the valley did not constrain peak discharge.

Failure and Experimental Cases: The failed dams cases were selected from Wahl (1998) where piping was identified as the failure mode; rockfill embankments were excluded. There was no further screening of data to match synthetic set characteristics. Added to these failure cases were the three experiments conducted by ARS (and from which soils information was used to construct synthetic set). The testing conditions of these 4-ft high embankments closely matched the synthetic set criteria describe in *initial conditions*. The selected cases and their peak breach discharges are reported in Table 3.

Table 3 Peak breach discharges for earthen dam failures for which piping was mode from Wahl (1998) and experiments conducted by USDA-ARS.

Case	Dam Height, ft	Peak Breach Discharge, ft^3/s
Apishapa, Colo.	112	6850
Baldwin Hills, Calif.	233	1130
Bradfield, England	95	1150
Davis Reservoir, Calif.	39	510
Frankfurt, Germany	32	80
Fred Burr, Mont.	34	650
French Landing, Mich.	40	930
Frenchman Creek, Mont.	41	1420
Kelly Barnes, Ga.	38	680
Lake Avalon, N.M.	48	2320
Lake Latonka, Penn.	43	290
Lawn Lake, Colo.	26	510
Little Deer Creek, Utah	86	1330
Lower Two Medicine, Mont.	37	1800
Teton, Idaho	305	65120
ARS Piping 1	4	110
ARS Piping 2	4	100
ARS Piping 3	4	40

RESULTS AND DISCUSSION

Peak breach discharges were tabulated for the completed model runs. In Figure 2 all results of WinDAM are shown, while the results corresponding to only the medium erodibility dams were plotted for BREACH. This was done because the predictions were essentially identical, and separate series could not be readily perceived on log-log plot.

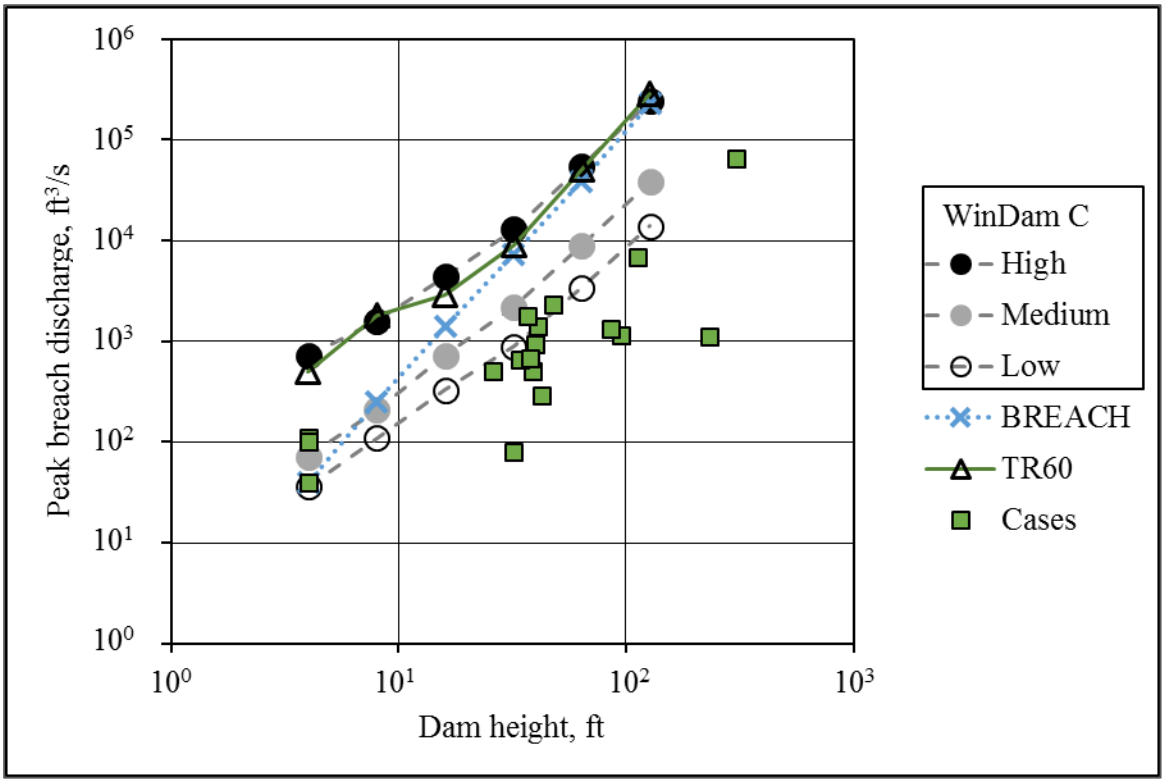

Figure 2 Peak breach discharge versus dam height for synthetic sets as predicted by WinDAM C and BREACH. For context also plotted are peak breach discharge for NRCS TR-60 and selected failure cases from Wahl (1998) and ARS research.

Relative to TR-60, BREACH arrives at very similar predictions for dams from 32 to 128 ft in height. WinDAM results for highly erodible dams track closely to the TR-60 relation throughout the full range of heights. Results for the more erosion resistant subsets (Medium and Low erodibility) roughly parallel the TR-60 series, but fall well below it, approximately an order of magnitude for the Low subset.

While plotted as points, there is often considerable uncertainty in the peak discharge. This uncertainty aside, note that none of the cases from Wahl plots above the Medium subset as predicted by WinDAM.

Times of peak discharge were also examined. While peak discharge exhibited little sensitivity in BREACH, there were discernible differences in time. The model tended to predict peak discharge of the highly erodible dams would occur in about twice the time as for low erodibility dams. For WinDAM, the time to peak was roughly 20 to 30 times greater for the low erodibility dams than the high erodibility dams. This was consistent with the behavior of physical models at USDA ARS.

CONCLUSIONS

Based on WinDAM results, for dams that are near the median storage, highly erodible material would be necessary for maximum discharge to approach that predicted by TR-60 equations. Conversely, if they were to breach under a similar scenario, most of the USDA Small Watershed Program structures would likely exhibit peak discharges well below TR-60.

The soils used to develop the synthetic sets exhibited considerably different erosion rates when tested. Note in the discussion that BREACH predicted the highly erodible dams would reach peak discharge *later* than more erosion resistant dams. For materials of higher plasticity, BREACH computes a critical shear stress similar to that found by jet erosion test. However, the representative diameter dominates the MPM-Smart equation. In BREACH, recall that roughness was estimated using soil gradation. This roughness was likely not representative of the form roughness that is more relevant to modeling flow rate. A user-selected roughness, however, further limits BREACH's sensitivity to a soil's characteristics. Because BREACH is unable to differentiate the behavior for these very different soils, this study further illustrates the difficulty in modeling detachment of cohesive materials as sediment transport.

The TR-60 equations and internal erosion cases suggest WinDAM is predicting in the correct order of magnitude. However, additional testing of the WinDAM model is needed to determine validity and bounds of application.

In closing, it is reiterated that the work presented here is part of the verification and validation testing by the developers. It is anticipated that WinDAM will be made available to a broader group for additional validation testing in the near future. As with any model, the results presented here require sound engineering judgment when applied.

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