WINDAM C: ANALYSIS TOOL FOR PREDICTING BREACH EROSION PROCESSES OF EMBANKMENT DAMS DUE TO OVERTOPPING OR INTERNAL EROSION

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HIGHLIGHTS

- The computational models comprising the current version of WinDAM, called WinDAM C, are summarized.
- WinDAM C estimates the response of an earthen embankment subjected to overtopping or internal erosion.
- WinDAM C is a model that quantifies erosion/breach processes observed in physical embankment failure tests.
- Understanding the current technology and limitations provides a basis for further model development.

ABSTRACT. *Internal erosion and overtopping erosion of earthen embankments are the leading causes for earthen embankment failures. Challenges like reservoir sedimentation, structural deterioration, rodent damage or tree root growth, and changing hazard classification from low to significant or high have arisen with aging dams. To address these challenges, new technology and tools for predicting the performance of homogeneous, cohesive earthen embankments during overtopping or internal erosion are needed. Windows Dam Analysis Modules (WinDAM) is a modular software application developed through collaborative efforts of the United States Department of Agriculture (USDA) Agricultural Research Service (ARS), the USDA-Natural Resources Conservation Service (NRCS), and Kansas State University (KSU) in response to this need. WinDAM uses a simple storage routing model to simulate flow through a reservoir and incorporates algorithms for predicting the progression of erosion resulting from embankment overtopping or flow through an internal discontinuity in the embankment. These algorithms are based on existing literature and data and observations from physical model experiments of homogeneous, cohesive embankments conducted by scientists at the USDA-ARS Hydraulic Engineering Research Unit in Stillwater, Oklahoma. The resulting computational model is a simplified representation of the observed process of progressive erosion that may lead to embankment breach. This paper reviews the components of the erosion/breach process and the way in which these components are quantified and integrated into the current WinDAM software, WinDAM C. The scope of application of the software, limitations, and computational assumptions are also discussed.*

Keywords. *Breach, Dams, Erodibility, Erosion Process, Failure, Internal erosion, Model, Overtopping, Piping.*

The U.S. National Inventory of Dams (NID) lists nearly 90,000 dams with the majority of these being classified as earth embankment dams. The United States Department of Agriculture (USDA), Natural Resources Conservation Service (NRCS) is listed as the engineer of record on nearly one third of the dams in the NID, many constructed since 1948 through the USDA Small Watershed Program authority. Changes in watershed conditions both upstream and downstream from these structures, combined with sediment deposition within the flood pool has led to an increased potential for overtopping during extreme events and an associated increased potential for loss of life and property in the downstream floodplain. Aging of the embankments including cracking and long-term seepage, rodent activity, and the growth of woody vegetation have increased the potential for failure through internal erosion.

Interest in the prediction of dam breach and the magnitude of the resulting flood increased sharply following dam failures during the last half of the 20th century. Some of the tools that evolved during this time are still used effectively today. These tools include predictive equations based on data from historic events (Wahl, 1998; Thornton et al., 2010)

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and application of process-based models utilizing the principles of sediment transport such as those described by Fread (1984, 1988). These tools focus on the prediction of peak discharge associated with breach and have been effectively used in floodplain mapping and related applications. However, they tend to be limited in their ability to provide information about the timing and physics of breach development or the impact of varying cohesive material properties.

More recently, engineers worldwide began to conduct research focused on the response of embankment dams to overtopping and internal erosion. This research included physical model studies involving relatively small-scale embankments (Hassan et al., 2004; Wahl and Lentz, 2011; Al-Riffai, 2014; Tabrizi, 2016; Ashraf et al., 2018; Alvarez et al., 2019), large-scale embankments (Vaskinn et al., 2004), and intermediate-scale embankments (Hanson et al., 2005a; Hunt et al., 2005; Ashraf et al., 2018; Ali et al., 2021). Vaskinn et al. (2004), Hanson et al. (2005a), Al-Riffai et al. (2014), Tabrizi (2016), Ashraf et al. (2018), and Alvarez et al. (2019) describe their dam overtopping studies. Wahl and Lentz (2011) present the results of tests focused on failure of canal banks, and Tabrizi (2016) also conducted research on levee overtopping. Hunt et al. (2007), Hanson et al. (2010), and Ali et al. (2021) present discussion of the expansion of the research described by Hanson et al. (2005a) to include internal erosion.

Because of these studies, new computational models of the breach erosion process that better reflect the observed behavior of cohesive embankments were developed. USDA's WinDAM (Windows Dam Analysis Modules) computer program incorporates modules for analyzing overtopping erosion of embankments, internal erosion of embankments, subsequent embankment breach development initiated by either erosion mode, and headcut erosion of earthen spillways. The individual modules and the program, as a whole, are both commonly described as models.

As a part of the ongoing research and development work, efforts have been made to validate and compare the various models. The models and associated software continue to evolve as the underlying processes become better understood and more data become available. Testing and refinement are expected to continue and result in improved model performance.

Development of model improvements in this field continues both within and outside of USDA, as demonstrated by several recent reviews and model evaluation efforts. ASCE/EWRI (2011) provides a discussion of breach processes and tools available in the industry at that time. The CEATI International Working Group on Embankment Dam Erosion and Breach Modeling (CEATI, 2017) presents the results of applying the HR Breach (Floodsite, 2020) and SIMBA (Hanson et al., 2005b; Temple et al., 2005) models to test cases of embankment overtopping representing both laboratory tests and actual dam failures. The SIMBA model used was a version of the overtopping model later incorporated into the WinDAM software, while HR Breach was developed by HR Wallingford (Floodsite, 2020). The CEATI (2017) report indicates that both models performed well on 5 of the 7 test cases.

Zhong et al. (2016) discusses the NWS BREACH model (Fread, 1988), the more recent HR Breach model (Floodsite, 2020), and DL Breach developed by Wu (2013). HR Wallingford has since developed EMBREA (West et al., 2018), a successor to HR Breach.

Zhong et al. (2019) conducted three large-scale physical model tests at the Nanjing Hydraulic Research Institute (NHRI), China, and developed a model to predict the overtopping-induced breach process of cohesive dams. They stated that the surface erosion and intermittent mass failure along a dam's axis and the formation of headcut and its migration in the longitudinal section were determined as the key breaching mechanisms for a cohesive dam due to overtopping. They also compared their model to the current version of WinDAM at that time (WinDAM B) and NWS Breach, and their sensitivity analysis showed that all three models were sensitive to soil erodibility. Overall, their proposed model and WinDAM B were more sensitive than the National Weather Service (NWS) BREACH model. The models were applied to selected test cases from the field and the laboratory.

Neilsen and co-workers used automated iterative application of the WinDAM software to evaluate the sensitivity of the results to various input parameters (Neilsen et al., 2012, 2015; Neilsen, 2013), and Neilsen and Cao (2017) continued this study using synthetic data sets to examine different computational models. Neilsen (2015) coupled fluid flows from computational fluid dynamics (CFD) models with the erosion models in WinDAM. Jia and Hunt (2016) present a finite element-based model (FEM) building on the conceptual framework of the overtopping portion of WinDAM. A future goal is to fully integrate CFD and FEM models on each time step.

Breach processes associated with embankment overtopping or internal erosion are complex and only imperfectly understood. To properly interpret the results of model comparison, validation, or sensitivity studies, it is necessary to understand the conceptual model on which the computational model is based, and the simplifications required in construction of the computational model. This report provides an overview of the development of the WinDAM software, its current capabilities, and how the physical processes are represented in the computations. Simplifications and limitations are emphasized to allow potential users to more easily determine the extent of applicability of WinDAM to their specific needs and to allow researchers to identify areas with greatest potential for refinement.

WinDAM Overview

WinDAM was developed by the USDA in collaboration with Kansas State University. The software was developed in stages reflecting the progress of research. The initial version, WinDAM A, focused on evaluation of whether flow overtopping the embankment would fail the slope protection layer (grassy vegetation or riprap) on the downstream slope (Temple et al., 2006; Temple and Irwin, 2006). WinDAM B extended the capability of the software to include modeling the continued erosion of the embankment after failure of the downstream slope protection, up to and through the initiation and development of a breach and uncontrolled release from the reservoir. Visser et al. (2010) and Visser et al. (2013a) discuss the overall capabilities of this version of the program. WinDAM C is the present version of the program, and it extends the scope of the model to progressive erosion along a defined flow path through a homogeneous embankment (internal erosion). Visser et al. (2013b) and Visser et al. (2015) discuss the overall capabilities of WinDAM C and its application. Expansion of the software capabilities and refinement and modification of the components were made throughout the WinDAM development process. This included incorporating the ability to analyze the breach potential of earth spillways using technology initially implemented in USDA's Water Resources Site Analysis Computer Program (SITES) (Temple et al., 2003; USDA NRCS, 2007).

The overtopping and internal erosion computational routines contained in WinDAM C were initially developed using the SIMBA (SIMplified Breach Analysis) software model (Hanson et al., 2005b; Temple et al., 2005). SIMBA was developed as a research tool to analyze the results of large-scale physical model tests conducted by the USDA, ARS. Validation and testing of the routines included application to data from laboratory tests and field data and comparison to other prediction models (Hanson et al., 2008; Tejral et al., 2009, 2012; CEATI, 2017). The routines were incorporated into WinDAM for real-world application.

Visser et. al (2013b) and Visser et al. (2015) present general discussions of the scope and application of WinDAM C. The computational capabilities of the current version of WinDAM C may be summarized as: 1) route a hydrograph through a reservoir having up to four spillway outflows with or without flow over the top of the dam and evaluate the potential for breach of up to three earth or vegetated earth spillways, 2) estimate the time of failure of vegetal (grass) or riprap protection on the downstream slope of an overtopped dam and/or estimate the rate of progressive erosion that may lead to breach as a result of overtopping of a homogeneous embankment dam, or 3) estimate the rate of progressive erosion resulting from flow through a defined horizontal flow path through a homogeneous earth embankment dam that may result in breach of the embankment. The computed outflow hydrograph includes outflow through an embankment breach, but outflow through a spillway breach is not modeled. The spillway breach component only determines whether a breach is initiated, not how it develops. The routines used to perform spillway or embankment erosion computations are simplified representations of the complex processes observed in laboratory tests and field experience. It is expected that as the physical processes become better understood, more sophisticated computational models will be developed, estimates improved, and applicability expanded to a wider range of conditions.

WinDAM Model

Reservoir Routing

Inflow and outflow hydrographs are imported from, and exported to, other software packages as appropriate. WinDAM routes the inflow hydrograph through the reservoir, but it does not perform hydrologic calculations for inflow hydrograph generation nor breach hydrograph routing computations in the downstream channel. The inflow hydrograph is routed through the reservoir using a level surface routing model with the assumption of stepwise steady state conditions. During computation, inflow, reservoir water surface elevation, and other conditions including the geometry of any developing breach erosion area are known at the beginning of each time step. Conditions at the beginning of the time step are treated as constant during the time step for purposes of erosion computation, allowing the geometry at the end of the time step to be computed as described in subsequent sections of this report. Discharge at the end of the time step may then be computed as a function of reservoir water surface; this allows the water surface elevation to be determined through a mass balance with both inflow and outflow averaged over the time step. Provision is made for preventing the linear averaging of discharge over the time step from introducing numerical instability into the computations through physically inconsistent overshoot of changing outflows.

Outflows may include a principal spillway, up to three auxiliary spillways, flow over the top of the dam, and flow through any developing breach area. The spillways may be represented by either elevation-discharge tables or by input of spillway properties. When represented by input of properties along with an elevation discharge table for the downstream tailwater, the impact of the tailwater is considered for each time step through iterative discharge computation. Reference ratings provided in the output are computed with the assumption of low tailwater since the total outflow for a given reservoir water surface elevation and thereby the tailwater elevation may vary with breach progression. WinDAM C does not allow gate-controlled spillways.

The principal spillway types that may be represented by properties are those typically used by the NRCS. These spillways may have single or two stage risers with single or multiple circular or rectangular conduits or may be of the hood inlet type with circular conduit. These are the same as those included in the SITES software (USDA NRCS, 2007). However, the computed ratings may differ slightly from those computed by SITES due to the inclusion of the effects of variable tailwater and the potential for orifice control at the conduit entrance. Interaction between the components is not considered when determining the impact of tailwater and whether inlet, orifice, or pipe control governs the spillway discharge. The rating computations are structured for properly installed reservoir principal spillways on earthen dams and may not be sufficiently refined for low flow culvert type application.

Auxiliary spillways may be represented by a trapezoidal channel of constant width. The spillway profile is entered as a station (distance)-elevation table along with a description of the flow resistance and its variation along the length of the spillway. Flow resistance may be expressed in terms of Manning's n or vegetal retardance curve index (Temple et al., 1987). The location of the hydraulic control for discharge calculations is the upstream end of the first reach downstream of the spillway crest for which normal depth flow would be supercritical for the discharge considered. When the tailwater is determined to be greater than the water surface elevation for critical flow conditions at the hydraulic control, the hydraulic control water surface is taken to be equal to the tailwater elevation. Spillway discharge is then determined through backwater computations based on energy balance. Hydrostatic pressure and uniform velocity distribution (energy coefficient of 1.0) are assumed throughout. Note that in seeking the location of the hydraulic control section, no check is made for submergence of a supercritical reach by normal depth in a downstream reach not accounted for in the specified tailwater elevation table. Therefore, configurations which might result in subcritical reaches downstream of a supercritical flow reach should be avoided.

For purposes of determining the discharge over the top of the dam, the dam crest may be represented by either a weir coefficient or a simplified cross-section representing the surface profile over which the flow occurs. In either case, the elevation of the dam crest representing the hydraulic control is allowed to vary along the length of the dam. The variation in elevation of the hydraulic control is specified by tabular input of station (distance)-elevation pairs that are then used as nodes for computation of discharge. When the discharge is to be determined from the typical cross-section, backwater computations using the approach described for auxiliary spillways are used to compute the unit discharge at each node. Flow resistance is again entered in terms of either Manning's n or vegetal retardance curve index and only frictional energy losses are considered. To compute total discharge over the dam, the unit discharge at each node is converted to an equivalent weir coefficient and discharge is integrated over the length of the dam assuming both elevation and weir coefficient to vary linearly between the nodes.

When overtopping causes progressive erosion, computation of the discharge through the area of the breach, if any, is unit discharge-based with the eroded geometry and effective breach area width determined as described later in this article. During breach initiation, the unit discharge in the breach area is computed as for other overtopped areas of the dam using the eroded cross section. Since the breach will tend to form at the point of maximum overtopping, the breach area unit discharge will always be greater than or equal to the maximum overtopping unit discharge. Once breach is initiated with lowering of the hydraulic control, energy losses are ignored, and the breach area unit discharge is computed using the assumption of hydrostatic pressure and an energy coefficient of 1.0 at the hydraulic control section. Flow depth at the control section is the greater of that implied by critical flow conditions or downstream tailwater. Total discharge through the breach area is computed as the product of the computed unit discharge and the breach area width. To obtain the total discharge associated with overtopping, including that through the breach area, the previously computed discharge associated with flow over the top of the dam is reduced by the product of the maximum overtopping unit discharge times the breach area width and added to the breach area discharge. This represents an approximation consistent with the approximations used in computing the progressive breach erosion as subsequently described.

When progressive erosion associated with flow through the embankment is considered, the flow path (conduit) is considered rectangular and horizontal through a homogeneous embankment. The initial width, height, and location of the conduit within the embankment are user specified. The initial conduit dimensions are treated as sufficient to generate turbulent flow, and the boundary roughness is considered constant in both time and space. Although progressive erosion as described in a subsequent section may change the width, height, and length, the conduit is assumed to retain its rectangular shape and horizontal orientation throughout the analysis. Discharge through the conduit may be the result of full conduit flow, free surface flow, or a combination of the two. Hydraulic control is assumed at the outlet of the conduit, and external tailwater is treated as for other discharge calculations. Manning's equation is used as for all flow computations within WinDAM and hydrostatic pressure and uniform velocity conditions are assumed. For full and partially full conduit flow, energy losses associated with the conduit entrance are ignored.

Auxiliary Spillway Erosion Analysis

WinDAM C software utilizes an extended version of the earth spillway integrity analysis model developed for SITES software (USDA NRCS, 2007). The underlying technology is that documented by USDA NRCS (1997) and discussed in USSD (2006). The original erosion model was extended through the joint efforts of the United States Department of Agriculture, the United States Army Corps of Engineers, and Kansas State University. The resulting SITES Spillway Erosion Model (SSEA) incorporated into WinDAM is described by Temple et al. (2003), Neilsen et al. (2004), and Wibowo et al. (2005).

The integrity of up to three earth spillways may be evaluated for a given reservoir routing. As implemented, SSEA is a post processor that evaluates earth spillway erosion using the spillway outflow hydrograph generated by the reservoir routing. Like SITES, the purpose of the analysis is to determine the potential for spillway breach. The spillway erosion analysis is not interactive with the reservoir routing, so no spillway breach hydrograph is generated.

Embankment Overtopping Analysis

The embankment overtopping evaluation component of WinDAM C assumes a homogeneous earth embankment in a rectangular non-erodible valley. The downstream face of the embankment may be bare soil or may be protected by a vegetal (grass) cover or riprap. For purposes of computing hydraulic attack, conditions are considered as known at the beginning of each time step and treated as constant over the time step. If erosion takes place during the time step, the geometry of the breach area is adjusted and used to compute the discharge and the hydraulic attack at the end of the time step.

Progressive erosion leading to a breach is quantified using the procedure introduced by Hanson et al. (2003) and later implemented in the SIMBA model (Hanson et al., 2005b; Temple et al., 2005) that was used to develop the computational model incorporated into WinDAM (Temple et al., 2006; Hanson et al., 2008). The erosion stages are: 1) failure of any slope protection and formation of a headcut on the downstream face of the embankment; 2) progression of the headcut through the crest of the embankment to initiate breach; 3) continued progression of the headcut into the reservoir with resulting lowering of the hydraulic control until the embankment is entirely removed in the breach area; and 4) widening of the breach area during draining of the reservoir. The end of stage 2 defines the breach initiation time; the time elapsed prior to the release of stored water. The end of stage 3 defines the breach formation time; the time elapsed prior to complete local removal of the embankment.

Stage one of the embankment breach process may be divided into two phases: a) the failure of slope protection, if any, on the downstream face, and b) surface erosion resulting in the development a headcut. The location of the surface failure and headcut development is taken to be the point of minimum embankment crest elevation the furthest from an abutment at the downstream edge of the crest. This location represents the combination of the point of maximum discharge over the embankment, and the minimum distance for headcut movement to initiate breach with the maximum potential for breach area widening during development. Note that this approach to erosion initiation implies that areas of concentrated attack such as toe, berm, and groin areas are submerged or otherwise protected since their effect is not evaluated.

To predict the time of phase 1 failure, it is assumed that normal-depth flow is developed on the downstream face of the embankment. If the slope is protected by vegetation, failure is evaluated similarly to phase 1 (surface) failure of vegetated earth spillways (USDA NRCS, 1997), applied to embankments as discussed by Temple and Irwin (2006). Failure of the vegetal cover by erosion through the vegetation occurs when a limiting value of the time integral of the erosionally effective stress is reached, or by direct destruction of the vegetation at a limiting value of gross stress.. Depth of erosion at failure is taken to be 0.15 m. Width of the failure area is taken as 1.4 times the depth. Any additional erosion during stage 1 is based on stress computed for flow over unprotected soil. The values of width and depth of the eroded area at failure are somewhat arbitrary based on observation, with the 1.4 value selected for consistency with computations of breach area widening as described below.

Riprap slope protection is evaluated based on an allowable unit discharge on the downstream face of the embankment (Temple et al., 2006). For typical slopes from 17% (6H:1V) to 40% (2.5H:1V) the unit discharge corresponding to failure is computed from the relation given by Robinson et al. (1998). For slopes between 17% and 10%, the allowable discharge relation is transitioned from that presented by Robinson et al. (1998) to the relation presented by Abt and Johnson (1991), which applies to the milder slopes (1% to 20%). For slopes from 40% to 50%, flow is assumed to be through the riprap and the current version of WinDAM uses the procedure described by Mishra and Ruff (1998) to predict failure. Riprap failure is assumed to remove the riprap to expose the underlying soil. Width of the initial failure is again taken to be 1.4 times the depth. Any additional erosion during stage 1 is based on stress computed for flow over unprotected soil.

When the downstream embankment face is unprotected implying exposed bare soil, surface erosion is assumed to initiate at the beginning of the first-time step in which the computed hydraulic shear based on normal flow depth on the slope exceeds the critical shear stress for the material. The depth of the eroding area is set to zero at the beginning of the time step. This results in a computed depth of local erosion at the end of the time step based on the computed surface erosion rate.

To compute surface erosion of exposed soil, the erosionally effective stress is taken to be the gross shear stress, implying that the flow is capable of detaching “particles” of the size governing flow resistance. Manning’s n representing the eroding soil surface is set to a value of 0.02. The erosion rate expressed in volume per unit area (erosion depth change) per unit time is computed using the excess stress relation:

$$\varepsilon_r = k_d(\tau_e - \tau_c) \quad (1)$$

where

τ_e = the erosionally effective stress on the soil (for bare soil conditions, total stress expressed in force per unit area),

ε_r = the soil detachment rate in volume per unit area per unit time,

k_d = a detachment rate coefficient (volume per unit of stress per unit time per unit of area), and

τ_c = the critical shear stress (force per unit area).

The detachment rate coefficient and the critical shear stress are material properties and are user inputs to the computational model. The history of this equation and determination of the material parameters from laboratory and *in situ* testing and correlation to basic soil properties and compaction conditions have been discussed by several authors (Hanson and Cook, 2004a; Hanson and Hunt, 2007; Hanson et al., 2011; Fell et al., 2013). Equation 1 is applied throughout WinDAM with the assumption of erosionally effective stress being equal to total hydraulic stress when applied to unprotected soil. Stage 1 surface erosion will continue to increase the depth and width of the eroding (breach) area until the depth of erosion is greater than the critical flow depth associated with the unit discharge in the breach area for that time step. Unit discharge is treated as constant over the width of the breach area. Additional stage 1 erosion following surface protection failure is treated the same as for the initial bare soil condition. The change in erosion depth over the time step is computed by multiplying the erosion rate, ε_r, times the length of the time step. To compute width change, each side of the eroding area is assumed to progress at approximately 0.7 times the rate of downward erosion. This rate is based on an approximation of the stress distribution in a rectangular channel reported by Lane (1955), and Hunt et al. (2005) confirmed the approximation was reasonable through observation of breach widening in their study. Widening is suppressed for the time step if the edge of the eroding area under consideration has reached an abutment or the elevation of the crest of the dam is greater than the elevation of the reservoir water surface at the edge of the eroding area.

When the eroded depth exceeds the critical flow depth while the elevation of the downstream tailwater is below the crest of the headcut, the flow will tend to develop a plunging action capable of causing the headcut to progress upstream into the crest of the embankment. This represents the end of stage 1 and the beginning of stage 2 of the process. The original embankment crest is treated as being erosion resistant, so the erosion depth during stages 1 and 2 represents the height of the developing headcut.

During stage 2 of the overtopping breach process, the headcut (breach area) widens, deepens, and progresses upstream through the crest of the embankment. While plunging flow continues, the downward erosion lowering the headcut base is again computed using equation 1. The applied stress in equation 1 is the greater of that computed for erosion on the slope below the headcut and that computed using the equations developed by Robinson (1992) for stress at the base of an idealized overfall. The width change of the breach area associated with the plunging flow action is taken to be equal to the headcut advance. For computation of headcut advance, WinDAM C allows the user to select either an energy-based or stress-based headcut advance model. The selection of which model to use will depend on a user's experience and the information available.

The energy-based model is semi-empirical. It is similar to that used in earth spillway analysis (USDA NRCS, 1997). This model, referred to as the Temple/Hanson model in the WinDAM software, is described by Hanson and Cook (2004b) and its implementation in SIMBA is discussed by Temple et al. (2005) and Hanson et al. (2005b). In this model, the advance rate is treated as proportional to the product of unit discharge and headcut height raised to the one-third power. The proportionality coefficient may be calibrated using data and experience with similar conditions or estimated from the detachment rate coefficient as discussed by Hanson et al. (2011).

Although the formulation of the Temple/Hanson model of headcut advance implies roughly equal energy in the approach and exit flows, no adjustment is made for tailwater unless the headcut is completely submerged. When the headcut is submerged by external tailwater or by the computed depth of flow away from the headcut, the headcut will be considered not to advance due to plunging action. This is true for the stress based advance model as well as the energy-based model.

The stress-based model is designated as the Hanson/Robinson model within WinDAM. This model is described by Hanson et al. (2001), and the WinDAM implementation is discussed by Hanson et al. (2011). This model is considered to more accurately reflect the observed headcut advance process and has the advantage of using only measurable material parameters. The physical process simulated by this model is episodic mass failure of the headcut resulting from undercutting of the face due to hydraulic stress associated with plunging action of the flow. The detachment rate of material leading to undercutting of the headcut is governed by equation 1. The resistance of the embankment material to mass failure for a given headcut height and extent of undercutting is represented by its undrained shear strength. Although the physical process represented is considered episodic, as implemented in WinDAM the process is simplified to be represented by an average advance rate computed for each time step.

As implemented in WinDAM, this model conservatively assumes the wash out of the material following a mass failure to be instantaneous. Therefore, the model is not strictly applicable when headcut heights are so great that the headcut is unstable without any undercutting erosion. Physical observations of headcut advance under these high headcut conditions are extremely limited, but the expected mode of advance would likely be erosion by cascading flow down the resulting unstable near vertical slope. Therefore, the headcut advance model implemented in WinDAM assumes an upper limit on the headcut advance rate equal to the rate associated with normal depth flow erosion on a ½ to 1 (H:V) slope using the assumptions previously described for bare soil. The ½ to 1 slope is based on the geometry assumed for mass failure as described by Hanson et al. (2001). In recognition of the fact that this represents only a crude approximation of the physics and actual geometry for high headcuts, no check is made as to whether there is sufficient energy available to generate normal depth flow on the slope above the base of the headcut.

Stage 3 of the breach erosion process begins when the headcut has advanced through the embankment crest and entered the upstream slope. Further advance will result in lowering of the hydraulic control with associated increase in discharge through the breach area. The time associated with the beginning of stage 3 is referred to as the breach initiation time. During stage 3, the headcut may continue to advance as in stage 2 or it may experience downcutting of the crest due to stress based erosion of the hydraulic control. When the flow is determined to be plunging, the downcutting of the crest is computed from the frictional hydraulic stress associated with critical flow conditions. When this rate of decrease in the hydraulic control elevation is greater than that associated with headcut advance due to the plunging action of the flow, this change in hydraulic control is considered to govern and the headcut is treated as having advanced the distance that would result in the equivalent drop in hydraulic control. Headcut height is allowed to decrease only when the headcut base has reached the dam base elevation.

After the elevation of the headcut base reaches the elevation of the base of the dam, further downward erosion of the base is suppressed and continuing headcut advance decreases the headcut height. This will eventually result in submergence of the plunging action driving the associated headcut advance rate to zero and causing the downward erosion of the crest to be computed using the stress-based approach described in the previous paragraph. When the elevation of the downstream tailwater is greater than the elevation of the water surface associated with critical flow over the crest of the headcut, the flow depth at the hydraulic control is taken to be the difference between the elevation of the tailwater and the crest of the headcut.

Stage three is complete when the headcut has advanced to the upstream toe of the embankment indicating complete removal of the embankment in the breach area. Stage 4 is limited to breach widening resulting from flow through the breach. Widening rates are computed from frictional stresses associated with flow through a rectangular section. Widening is suppressed when an abutment boundary is encountered.

Internal Erosion Analysis

Like the overtopping component, the internal erosion component of WinDAM C is a simplified representation of the physical processes observed during intermediate- to large-scale tests. The assumptions of a homogeneous embankment and a rectangular valley with non-erodible boundaries are again applied. As noted in the discussion of discharge computations, the initial condition for internal erosion computations is a horizontal flow path (conduit) through the embankment. The flow path is assumed to be rectangular and large enough to generate turbulent flow such that the Manning flow equation may be applied. The flow path is assumed to remain horizontal and rectangular with a width and height that vary in time but are constant over the entire length as progressive erosion takes place. The initial location of the flow path is user specified as is the initial width and height.

Visser et al. (2015) present a general discussion of the computational model as implemented in WinDAM C. Two types of progressive erosion are tracked. These are expansion of the eroding conduit due to frictional hydraulic stress and the development and subsequent advance of a headcut that may form at the outlet. These actions are considered to take place simultaneously and either may ultimately dominate the breach process.

Rate of expansion of the eroding conduit is based on equation 1 with the erosionally effective stress taken as the average frictional hydraulic stress over the wetted boundary of the conduit. This is true whether the conduit is flowing full over the entire length, partially full (free surface flow) over the entire length, or full over only a portion of the length. The hydraulic stress on the conduit boundary is computed using the Manning equation with a roughness coefficient for the embankment material of 0.02. For full and partially full conduit flow, the length of the conduit is taken to be the distance from the intersection of the upper surface of the conduit with the upstream face of the dam to the computed position of the headcut. The conduit is considered to expand equally in all directions unless a non-erodible boundary is encountered. For partially full conduit flow, the entrance of the conduit is taken to be the intersection of the water surface with the upstream face of the embankment (the most upstream point where the flow is fully contained within the conduit area) and the conduit is not expanded upward. The upper surface of the conduit is considered to remain intact so long as the conduit is flowing full over any of its length. If the conduit is computed to flow only partially full over the entire length and the width of the conduit is wider than twice the distance between the conduit and the top of dam, the top is considered to have collapsed and the conduit cannot again flow full.

A headcut may form at the intersection of the lower surface of the conduit with the downstream face of the dam. Headcut formation is computed as for overtopping with a bare soil slope. Any erosion protection on the downstream slope is considered compromised and therefore ignored. Width of the headcut is considered to be controlled by the conduit width unless the headcut has advanced into the upstream face of the dam and the conduit no longer exists. At that point, widening is treated as for stages three and four of the overtopping breach. The hydraulic control for discharge computations is considered to be at the position of the headcut and, with the exception of tailwater effects, conditions downstream of the headcut are not considered.

Application

WinDAM is an analysis tool that may be used to route a hydrograph through a reservoir with or without evaluation of overtopping or internal erosion. However, the primary intended use of WinDAM C is the analysis of earth embankment dams that may be potentially breached by progressive erosion as a result of overtopping or flow through the embankment (internal erosion). As previously noted, physical tests were conducted in the USDA ARS outdoor laboratory to determine the breach characteristics of embankments subjected to attack through overtopping and internal erosion. The test setup was described by Hanson et al. (2003) along with a description of the overtopping tests. A description of the internal erosion tests was presented by Hanson et al. (2010) and further detailed by Ali et al. (2021). Results of these tests have also been discussed in other publications as indicated in previous sections of this report. More detailed information on the embankment materials and flow conditions are available for these types of laboratory tests than are generally available for field conditions where failure has occurred.

ARS Embankment Overtopping Test 1

Construction of the embankment for overtopping test 1 was described by Hanson et al. (2003, 2005a). The embankment was nominally 2.3 m high with a 4.6 m crest width and 3:1 upstream and downstream slopes. It was constructed of a non-plastic SM material compacted in 0.13 m lifts. The soil materials were considered homogeneous with sufficient cohesion to form a headcut. The test section for initial overtopping was 1.8 m wide, but during the breach process, widening beyond the initial 1.8 m overtopping width could occur. Poor-quality vegetation on the slope at the time of testing provided negligible erosion protection. Figure 1 shows the embankment during testing.

Figure 1. ARS embankment overtopping test 1 with the headcut entering the embankment crest (after Hanson et al. 2003).

Hanson et al. (2005b) presented the results of applying SIMBA to the data from this test using the energy based headcut advance model that is essentially that referred to as the Temple/Hanson Model in WinDAM C. Hanson et al. (2011) presented the hydrograph resulting from applying WinDAM B using the Hanson/Robinson headcut model to these data. The example herein reproduces that application using WinDAM C and provides additional detail related to output from the computations.

Soil properties for input to WinDAM C are:

$$k_d = 10.2\ \text{cm}^3/(\text{N s}) \text{ or } 5.8\ (\text{ft/h})/(\text{lb/ft}^2)$$

$$\tau_c = 0\ \text{Pa or } 0\ \text{lb/ft}^2$$

$$\gamma_t = 1.87\ \text{g/cm}^3 \text{ or } 117\ \text{lb/ft}^3$$

$$c_u = 10\ \text{kPa or } 213\ \text{lb/ft}^3$$

k_d and τ_c are as previously defined and were based on measured erodibility tests (JETs). γ_t is the total unit weight of the in-place embankment material, and c_u is the undrained shear strength of the material. WinDAM requires all input values to be in U.S. customary units. The total unit weight is used in computing the driving force for mass failure of the headcut, and the undrained shear strength is used in determining resistance to mass failure as described by Hanson et al. (2001) and Hanson et al. (2011).

This embankment was subjected to an inflow hydrograph as shown in figure 2. A headcut formed, moved the 4.6 m through the crest and entered the reservoir forming an essentially full breach. A comparison of the observed headcut migration and that predicted by the WinDAM C simulation is shown in figure 3. Figure 4 presents a comparison of the observed and predicted headcut width during the test. The predicted outflow hydrograph for the breach is shown in figure 2 along with the inflow hydrograph and measured values of the outflow through the breach area. All values show relatively good agreement for these controlled laboratory conditions.

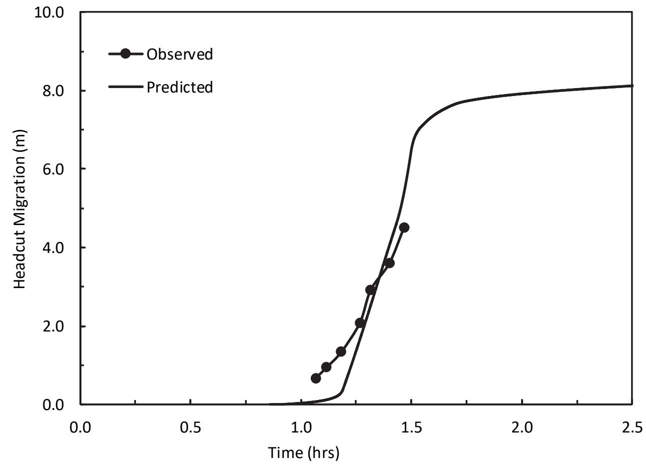

Figure 3. Observed and predicted headcut migration for overtopping test 1.

ARS Internal Erosion Test P1

Internal erosion test P1 is described by Hanson et al. (2010) and Ali et al. (2021). The test embankment was constructed in the same test facility as overtopping test 1 described above. However, for this test, a 43 m long sharp crested weir was used to form a spillway for the reservoir. The test P1 embankment was constructed of SM material similar to that used in the overtopping test. The soil materials of the embankment were considered homogeneous and had sufficient cohesion to form a headcut. The embankment was constructed to a height of 1.3 m in 0.09-m lifts. The slopes were nominally 3(H):1(V), and the crest width of the embankment was approximately 1.8 m. During construction, a 40-mm diameter horizontal pipe was embedded into the embankment at an elevation of 0.4 m above the base. This pipe was then removed at the beginning of the test to form the initial internal erosion discontinuity. Figure 5 shows the embankment at the beginning of the test.

WinDAM C was applied to these test conditions with the Hanson/Robinson model specified for headcut advance evaluation. Soil properties for input are:

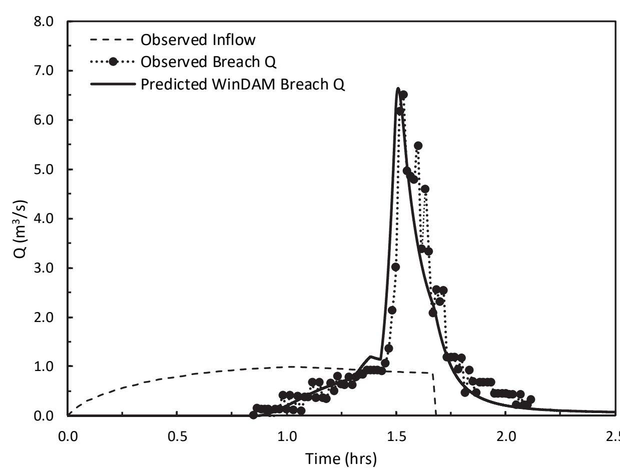

Figure 2. Observed inflow and outflow and predicted outflow for overtopping test 1.

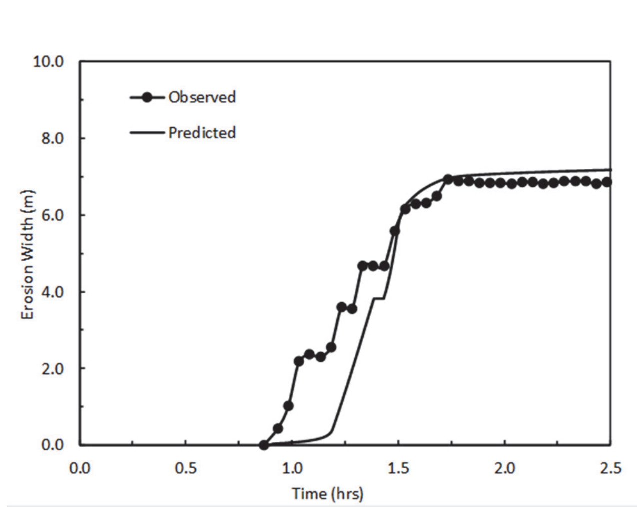

Figure 4. Observed and predicted erosion width for overtopping test 1.

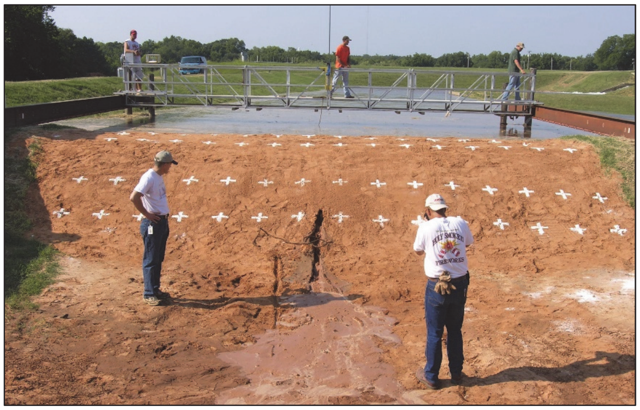

Figure 5. ARS embankment internal erosion test P1 at test initiation (after Hanson et al., 2010).

$$k_d = 120\ \text{cm}^3/(\text{N s}) \text{ or } 70\ (\text{ft/h})/(\text{lb/ft}^2)$$

$$\tau_c = 0.14\ \text{Pa or } 0.003\ \text{lb/ft}^2$$

$$\gamma_t = 1.91\ \text{g/cm}^3 \text{ or } 119\ \text{lb/ft}^3$$

$$c_u = 13\ \text{kPa or } 270\ \text{lb/ft}^2$$

where the variables are as previously defined. k_d and τ_c values were again determined using the JET device and methodology. It is noted that, although the test material was generally similar, the measured erodibility (k_d) for this embankment was an order of magnitude higher than for the overtopping test.

The predicted outflow hydrograph through the eroding (breach) area is shown in figure 6 along with the measured inflow and breach area outflow hydrographs. Both the observed and predicted breaches were relatively rapid. The breach hydrograph predicted by the WinDAM C simulation occurred more rapidly than the observed breach. The earlier breach time predicted by the simulation is also reflected in the plotted values of simulated and observed breach widths as shown in figure 7, although the nature of the width increase appears relatively consistent. The earlier simulated breach also meant that the inflow at the time of the predicted breach was less than the inflow at the time of the observed breach. Simulated peak outflow was lower than the observed outflow even though the embankment was predicted to erode more rapidly than observed. The specific reasons for the differences in predicted and observed performance are not clear at this point and it is recognized that additional validation and refinement of the model is appropriate.

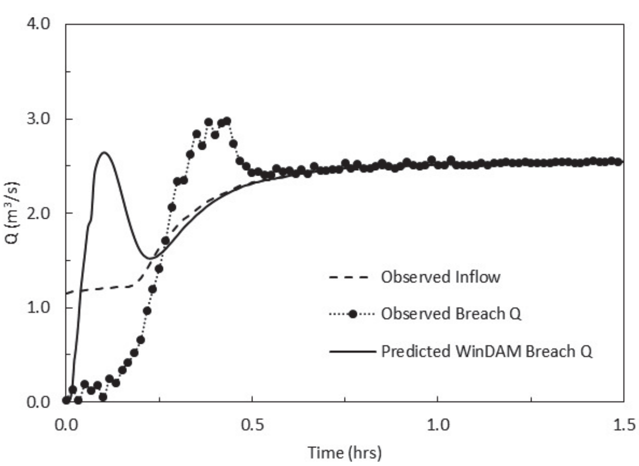

Figure 6. Observed inflow and observed and predicted outflow for internal erosion test P1.

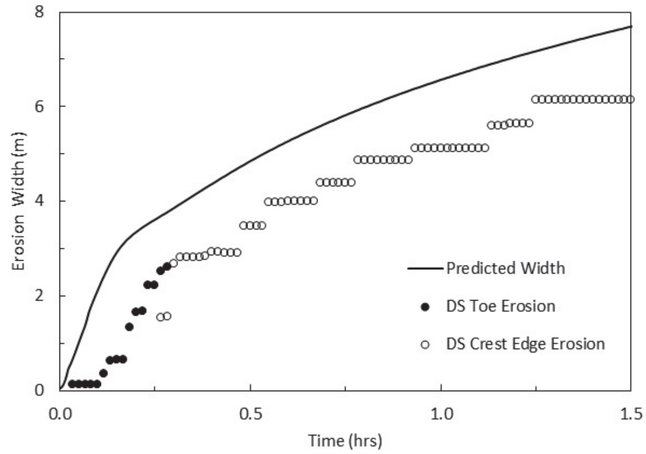

Figure 7. Observed and predicted breach width for internal erosion test P1.

Model Scope and Need for Additional Study

As previously indicated, the failure processes associated with embankment erosion and the associated breach are only imperfectly understood and WinDAM C addresses only a subset of the possible failure scenarios. Additional research is needed to both refine and expand the current computational model(s).

WinDAM C is intended for application to homogeneous earthen embankments with sufficient cohesion to allow formation and advance of a headcut. When considering erosion associated with embankment overtopping, only breach associated with headcut formation and advance is considered. The effects of discontinuities on the downstream slope such as berms, groins, or the toe of the embankment are not considered in computations associated with headcut formation. When evaluating internal erosion, the embankment material is also assumed to have sufficient cohesion to allow formation of a flow path capable of sustaining turbulent flow. Such a flow path is assumed to exist at the initiation of computations and only erosion associated with expansion of this flow conduit and development and advance of a headcut at its outlet is considered. Formation of this flow conduit is not addressed in the current WinDAM C model. Erosion is considered to take place entirely within the earthen embankment with the abutments and foundation treated as non-erodible. Potential interaction of the described processes with other failure modes, such as foundation erosion or embankment sloughing, is not considered for either the overtopping or internal erosion models. Models are needed which can appropriately be applied to zoned embankments or foundation erosion and evaluate such things as formation of the internal erosion conduit or slope protection using blocks or reinforced vegetation.

The erosion processes described in the preceding paragraph are considered generally applicable to erosion of canal banks and levees. However, WinDAM in its present form was developed as a "first cut" at quantifying these processes for application to embankment dams and includes reservoir routing in the computations. In its present form, it is therefore limited in its application outside of that intended purpose.

Further study is also needed to evaluate the impact and need for refinement or replacement of various simplifying assumptions and approximations applied in the development of the present WinDAM model. These simplifications and approximations were considered useful in the development of the "first cut" dominant process model(s), but they are expected to require modification as these models are refined or replaced. Related studies may include validation, statistical evaluation, and sensitivity analysis of the existing model(s) as well as fundamental research on the underlying processes. Simplifications and approximations appropriate for further study include, but are not limited to, those discussed briefly in the following paragraphs.

WinDAM C approximates the valley containing the embankment by a rectangular section with the abutments and foundation treated as non-erodible. The breach area is also considered to be rectangular (vertical sides) as is the internal erosion conduit. The internal erosion conduit and the embankment foundation are considered horizontal. The internal erosion conduit is assumed to remain horizontal and rectangular with constant cross section over its length throughout the erosion process and spatially averaged stress is used in computing rate of conduit expansion.

Erosion of the embankment material is considered detachment limited with the flow capable of removing the detached material from the area in which progressive erosion is taking place. To the extent that detachment is computed directly, it is considered stress driven and equation 1 is applied. In computing stress associated with flow, Manning's equation is applied with an n value of 0.02, and the total stress so computed is considered effective in generating erosion (stress used in equation 1). Although this approach is believed to be generally consistent with the assumption of a detachment limited soil erosion process in turbulent flow, the entire area of flow resistance and the effectiveness of the associated stress in generating detachment during the erosion process is considered by the authors to warrant further fundamental research.

Other simplifications and approximations were required in development of the computational model(s). Some of these are noted elsewhere in this report. To the extent possible, these were applied in a fashion consistent with any associated errors resulting in increased rather than decreased erosion. An example is the restriction that as a headcut moves through the upstream slope of the embankment, the crest is always at the intersection of the crest elevation with the embankment slope and the headcut height is not allowed to decrease until the base of the headcut reaches the elevation of the base of the embankment. It is recognized that this may not always be the case in actual failures, but since erosion computations are considered approximate, it was considered preferable not to allow headcut washout to be predicted when it might not actually occur. It should be noted, however, that this approach to application of the simplifications and approximations does not guarantee that the estimated erosion or breach outflow will be greater than the actual.

The WinDAM C model is intended to provide an estimate of the performance of earthen embankments within the identified scope of application. It should be noted not all details of the computations are included herein, but this manuscript provides an overview of the model. It is hoped that research will continue, allowing the present models to be refined and/or new models to be developed that are applicable over a broader range of conditions and provide improved estimates of performance.

Summary

The WinDAM software was developed as an analysis tool for earth embankment dams. It may be used to route a hydrograph through a reservoir, considering outflow through one principal spillway, three auxiliary spillways, and flow overtopping the dam. Integrity analysis may be performed on earth auxiliary spillways to determine the potential for breach, but a breach hydrograph associated with spillway failure is not calculated and any breaches of spillways do not affect the routing results. Hydrographs can be developed for breaches of earth embankment dams caused by headcut erosion from flow over the top of the dam or internal erosion and associated headcutting along a defined flow path through the embankment.

The earth embankment breach analysis that is the focus of WinDAM C is the result of research including embankment overtopping and internal erosion physical model tests conducted in the outdoor laboratory. The computational model quantifies the observed erosion processes in simplified form. WinDAM C is applicable to homogeneous earth embankments displaying sufficient cohesion to allow headcut formation. Measurable properties of the embankment material are used to compute the rate of erosion progression.

The computational models for both embankment overtopping and internal erosion prediction are first generation efforts at simulating anticipated embankment performance. Simplification of the complex erosion processes was required in the development of the computational models and, to the extent possible, the attempt was made to have potential errors associated with these simplifications result in over prediction rather than under prediction of erosion rates. The resulting computational models are believed to be an effective representation of the dominant processes suitable for use in estimating erosion rates and discharges. However, because erosion processes are complex and only imperfectly understood, professional judgment is essential in the interpretation of results. As the processes become better understood, it is expected that more refined models with a wider range of applicability will be developed. WinDAM C does not address all possible modes of failure, and the user is cautioned to evaluate their particular situation to make a judgment as to whether utilization of this software is appropriate.

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