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EROSION OF EARTH SPILLWAYS

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ABSTRACT

The Natural Resources Conservation Service (NRCS) Water Resources Site Analyses computer program, Sites, contains a vegetated earth spillway erosion prediction model. Since the beta release of Sites in 1996, the program has been successfully applied in the analysis of a number of existing spillways as well as in the design and re-design of NRCS flood retarding structures. Work has also continued on refinement and extension of the model's erosion prediction relations through the evaluation of field data from spillways representing a wider range of conditions than were available during the original model development. To assist in this refinement effort and to make the spillway erosion model more easily applied to a wide range of conditions, the model code has been extracted from the more general Sites program and modified to make application more flexible. Changes made to date include upgrading the code to take advantage of features of FORTRAN 90, increasing the number of hydrograph data points that may be used in computation, providing a utility to import hydrograph data from HEC models, and providing the user additional flexibility in defining the headcut advance threshold and rate parameters. This paper presents the general principles of the Sites spillway erosion model and the implications of these modifications as they relate to its application. Model assumptions, application limits, strengths, and weaknesses are discussed in the context of the modifications and the ongoing research efforts.

INTRODUCTION

Background

Over the past 50 years, the United States Department of Agriculture has assisted in the construction of approximately 11,000 flood control dams through the programs carried out by the Natural Resources Conservation Service (NRCS: formerly SCS). The majority of these structures utilize vegetated earth auxiliary spillways to pass major floods around the dams. Experience has shown this type of spillway to generally perform well. However, the criteria used for design of many of these spillways (SCS, 1973) were severely limited in their ability to reflect the physical processes associated with the erosion occurring during extreme flood conditions. Therefore, the Agricultural Research Service (ARS), as the research arm of the USDA, began in the 1980's to work with NRCS to gather data from field experience and to study spillway erosion processes in the laboratory (Temple et al., 1993). As a result of this effort, a three-phase model of the

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spillway erosion process was developed and incorporated into NRCS dam design software, Sites. The purpose of the model as developed and implemented is determination of the breach potential of a vegetated earth spillway during the passage of a freeboard design storm.

The three-phase model of spillway erosion and its implementation in the Sites software is documented in NRCS (1997). Phase one of the spillway erosion process is the failure of the vegetal cover, if any, and development of concentrated flow. The equations describing this phase of the process are based on erosionally effective stress combined with a linear excess stress detachment rate model (Temple and Hanson, 1994). This portion of the model was calibrated for field conditions using data from spillways that had experienced various levels of hydraulic stress. Phase two of the process is the concentrated flow erosion that takes place following local removal of the vegetal cover and/or increased local erosion. The equations describing this phase are also based on the linear excess stress detachment rate model under the assumption that the vegetal protection has been locally removed over an area sufficient to allow full concentration of the flow. The increased local erosion continues until a headcut is formed. Phase three of the erosion process consists of the upstream advance and deepening of the headcut that occurs as a result of the plunging action of the flow over the vertical or near-vertical headcut face. Like phases one and two, the relations used in quantification of headcut deepening during phase three are based on a linear excess stress detachment rate model. The headcut advance component of the model uses a linear excess hydraulic attack formulation similar to the excess stress detachment rate model applied to phases one and two. However, the computed hydraulic attack for headcut advance is based on energy rather than stress. Computation of the resistance of the geologic materials to hydraulic attack is based on a headcut erodiblity index (NRCS, 2001). As applied, this index is that previously used by Kirsten (1988) to predict the resistance of geologic materials to excavation. Details of the development of the headcut advance prediction model are given by Moore et al (1994) and Temple and Moore (1997). Because the erosion process being described is a local phenomenon that may develop at different times at different locations depending of the spillway profile and surface conditions, the three-phase model is applied repeatedly to determine the condition that poses the greatest risk of spillway breach.

The NRCS dam design software that the spillway erosion model is integrated into, Sites, is a descendent of the DAMS2 software used in the design of many of the NRCS-assisted watershed dams (Temple et al, 1995). The DAMS2 software performed flood routing through a reservoir site using the curve number approach for runoff volumes and was capable of determining design parameters such as the auxiliary spillway crest and top of dam elevations according to NRCS criteria (SCS, 1985). The Sites software retains all of the capabilities of the earlier DAMS2 software with the added capability of performing vegetated earth spillway analyses using the three-phase erosion model. In developing Sites, the DAMS2 code was updated in a number of areas, including the computation of vegetated auxiliary spillway ratings with the variation of flow resistance with discharge considered. A user interface in the form of an Integrated Development Environment

(IDE) was also added. This software is currently being used by NRCS and others for design and analysis of watershed dams.

<u>Strengths and Limitations of Sites</u>

The three-phase spillway erosion model implemented through the Sites software has proven to be an effective tool for vegetated earth spillway design and analysis. However, the erosion model represents a first effort to quantify the processes, and the Sites software is somewhat specialized to the needs of watershed dams of the type constructed with the assistance of the USDA. Earth spillways are also used on other types of dams, and work on furthering our understanding of the erosion processes has continued (Wibowo and Murphy, 2002). The work discussed in this report was undertaken for the purpose of refining the present erosion model and making it suitable for application to a wider range of conditions. The scope of the present effort is best understood in the context of the strengths and weaknesses of the current Sites model and software.

Strengths of the spillway erosion model are the result of the focus on underlying physical processes and of the extent of the field data and analyses used during its development. Specific strengths of the model and the software include:

- The overall erosion process is divided into sub-processes for quantification. Each of the three phases identified were quantified based on the physics dominating that phase.
- The model employs easily understood and tested approaches to the extent possible in quantifying the erosion process for each of the phases. This allows users to more readily understand the implications for application to specific problems.
- The model was calibrated using relatively extensive field data and validated using data not included in the calibration. Although theory and laboratory data were employed in model development, field data were used extensively in the final calibration.
- The model requires minimal data input, but is capable of addressing complex geologic conditions. The model was developed to predict breach potential of vegetated earth spillways representing a wide range of geologic and hydrologic conditions.
- The Sites software can develop an auxiliary spillway rating with consideration given to the variable flow resistance associated with the use of grass cover in the control section.
- The Sites software integrates a number of additional design and routing calculations with the spillway analysis, allowing evaluation of the impact of spillway configuration on overall design to be performed in a single step when NRCS criteria is applicable.

Limitations of the model are associated primarily with the degree of simplification and the assumptions required to allow broad application with minimal input data. These limitations and weaknesses include:

- The model is semi-empirical and calibrated using data from USDA spillways. Extrapolation of the model to spillways with much larger discharges and flow durations requires appropriate caution and an understanding of the erosion processes. The model was developed for application to vegetated earth spillways free of reinforced barriers or sills.

- The model is two-dimensional with erosion width and flow concentration accounted for through simplifying assumptions. These assumptions are most applicable when the erosion is initiated in reaches where the flow is supercritical.
- All phases of the erosion process are assumed to be detachment limited. Although this assumption appears to apply to a wide range of spillway conditions, it may not always be valid. Sediment transport may limit erosion for conditions such as long subcritical flow reaches through fine noncohesive materials.
- A low tailwater condition is assumed for headcut advance and deepening computations. This is generally a conservative assumption (extent of erosion tends to be over estimated) and requires that the user enter a maximum erosion depth (valley floor elevation) to terminate computed downcutting.
- Spillway width, and therefore unit discharge, is considered constant over the length of the spillway.
- Incorporation of the spillway erosion model into legacy routing software imposes additional limitations on flexibility with respect to such parameters as the time increment used in computations and the number of geologic materials used to represent the spillway profile.
- As implemented, the spillway hydrograph must be generated by a reservoir routing within the software. Use of an externally generated hydrograph with this software requires use of a false reservoir with zero storage.

Sites, as with all software and computational models describing complex processes and their interaction, is best applied by informed professionals who have an understanding of the processes being simulated.

SITES SPILLWAY EROSION ANALYSIS

Scope

The Sites Spillway Erosion Analysis (SSEA) effort was undertaken as a cooperative effort of ARS, the United States Army Corps of Engineers (USACE), and Kansas State University (KSU) to address some of the specific weaknesses that were identified for the current software. The first step in the process was to extract the spillway analysis portion of the software from Sites. This adds flexibility and allows proposed computational refinements to be evaluated without impact on application of the Sites software. This stand-alone package is what is referred to as SSEA. In its present form, the SSEA software is intended for use as a research tool for model evaluation and for field application by users not wishing to utilize the runoff and routing portions of the Sites software. Direct use of Sites will continue to be advantageous to most users involved in design and analysis of dams using NRCS criteria.

The structure of the Sites code limited the number of data points that could be used in describing both the hydrograph and the geologic materials in the spillways. The creation of a stand-alone package allowed these limits to be substantially expanded. Within Sites, the number of geologic materials used to describe the spillway profile was limited to 10 in-place materials with a maximum of 20 points used to describe the surface of each material. SSEA raises the limit to 100 materials with up to 100 points used to describe the surface of each. The number of hydrograph points is expanded from the maximum of 500 allowed in Sites to 3000 in the SSEA software. These changes make the model more applicable to larger spillways and storms generating long duration flows through the spillways.

Separation of the spillway erosion analysis from the reservoir routing has the disadvantage of requiring external routing of the flow to develop the hydrograph through the spillway. However, it increases the flexibility of application by allowing the user to select the routing software or procedure used. Procedures for importing output from HEC models and Sites into SSEA have been documented in addition to the manual hydrograph input option. Hydrograph input may be in the form of a variable time increment, but must be converted to a constant increment before calculations are performed. The time increment of the hydrograph is used for incremental erosion calculations, thereby giving the user control over the time increment used. Provision is made in the IDE for convenient change of the hydrograph time increment.

In some instances, it may be possible to improve the headcut advance prediction by using data from headcut advance observed in similar material. Studies by the USACE have indicated some variation in the slope and position of the headcut advance threshold and rate curves for erosion resistant materials (USACE, 1995; Perlea et al., 1997; Wibowo and Murphy, 2002). To allow the impact of these variations to be examined, the computational model was modified to allow the user to control the constants governing the relation of headcut advance threshold and rate to the headcut erodibility index. This also allows use threshold and rate curves developed from specific experience with similar spillways. The option to use the curves originally established by USDA is retained, and provision is made for visually comparing the modified threshold and rate curves with those originally developed.

In addition to changes influencing computations as described above, extraction of the spillway analysis model allowed refinement of the IDE output data display. The summary table created by the IDE includes information on the time and location of critical headcut formation, and, in the case of predicted breach, the timing of that breach. Graphical representation of the hydrograph, geology, and the predicted erosion are similar to that provided by Sites.

Software Status

At the present time (April 2003), a beta test version of the SSEA software is available for general use and may be downloaded from pswcrl.ars.usda.gov. This software contains the modifications to the Sites model described in the previous section. As a test version, the user is responsible for its use, including verification of results.

Required inputs for application of the test software are:

1. A hydrograph describing flow through the spillway to be evaluated,
2. Spillway geometry, including spillway width and surface profile,
3. A description of spillway cover and surface conditions for the entire length of the spillway,
4. A description of the location and properties of all geologic materials potentially exposed during erosion, and
5. Selection of the headcut advance threshold and rate relations to be used in computation. Options are the USDA equations used in Sites or user input coefficients.

Output consists of:

1. A text file describing the input and the predicted performance of the spillway,
2. Graphical display (plots) of the hydrograph, the geology, and the predicted extent of erosion, and
3. A summary table that may be customized to display selected input and output variables for multiple input files. This summary table allows convenient comparison of design alternatives and graphical display of the sensitivity of results to changes in input parameters.

As with the parent Sites model, the primary purpose of this software is determination of the breach potential of the spillway. The three-phase erosion model is applied iteratively to determine the erosion scenario most likely to result in breach. Each headcut is evaluated as if it were the only erosion taking place in the spillway at that time. If a headcut is predicted to cause breach, the time of that breach is reported and computations for that headcut are terminated. The reported results include the formation and final locations of the headcut progressing the furthest upstream, the formation and final location of the headcut having the greatest overfall height, and a composite eroded surface based on all headcuts evaluated. Note that the composite eroded surface represents only a crude estimate of the extent of erosion with the focus of the computations being on the potential of a headcut to breach the spillway. Breach is defined as any lowering of the spillway hydraulic control. Stopping computations when breach is predicted allows the hydrograph to be treated as independent of the extent of erosion.

<u>Ongoing Research and Refinement</u>

Efforts to refine the computational model and to expand applicability of the software are continuing. Efforts are underway to combine Data from USDA and USACE spillways with laboratory test data for the purpose of refining the headcut threshold and advance relations. These data will include the data on which the original USDA relations were based, plus data acquired subsequent to the original model development. Analysis of these data will be completed prior to any formal release of the SSEA software. Appropriate guidance will be developed for use of the additional flexibility in the determination of headcut advance threshold and rate.

The potential for optimizing the computational time step for various hydrologic and geologic conditions is being evaluated. As previously noted, the present model uses the time step of the input hydrograph for computation of erosion. For conditions of high discharge and weak materials, excessive erosion during a single time step may violate model assumptions of constant material conditions over the step. It is anticipated that future versions of the software will provide guidance and/or automatic time step adjustment.

Alternatives for including the impact of changing spillway width and of exit channel curvature are being considered, although no resources are presently committed to related software modifications. The most direct means of including these effects is to allow unit discharge to vary with location along the profile of the spillway. An option to allow this variation is likely to be included in future versions.

The problem of spillway erosion is complex, and the relations used in quantification of the processes are greatly simplified. Because the present model is based on the assumption of detachment limited erosion, processes such as erosion generated by abrasion or sediment transport impacts on erosion rate are not accounted for. Additional guidance is needed to determine when these actions become important and how to best address their effects. The present headcut erodibility index was developed to measure resistance to excavation. The potential exists to refine this index to more effectively represent the forces resisting headcut movement. It is expected that as advances are made in these areas, the computational models will continue to be refined and spillway performance prediction improved.

SUMMARY

SSEA and its parent, Sites, are first generation models for use in predicting vegetated earth spillway performance. These models are based on a three-phase approach with each phase represented by threshold rate relations that are integrated over the time of the hydrograph to predict headcut development and advance. Multiple erosion scenarios are evaluated to identify the potential for spillway breach.

Although the present models are effective tools, the relations are simplified representations of complex processes. Work is ongoing to refine the computational model and to advance our understanding of the processes involved. The computational models will continue to evolve as advances are made in these areas.

The SSEA software is presently available in test format. It will have advantages over the earlier Sites software for research application and in-depth analysis where the additional flexibility in headcut advance threshold rate prediction is beneficial. The increased array sizes in SSEA may be needed for representation of large geologically complex spillways and long duration flows. The separation of the software from the reservoir routing portion of Sites will make it more convenient for users who wish to use models other than Sites for development of the spillway hydrograph, but less convenient for users doing analysis under NRCS criteria.

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