Headcut Advance Prediction for Earth Spillways

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Abstract. *New technology for predicting the performance of earth (soil and rock) spillways has been developed through the joint efforts of the Agricultural Research Service (ARS) and the Natural Resources Conservation Service (NRCS). This technology has been computer coded, and the resulting computational model incorporated into NRCS software. As a part of evaluating the potential for spillway breach, one component of this model predicts headcut advance within the spillway. This component utilizes an energy-based parameter to describe the erosive attack and a headcut erodibility index to describe the resistance of the geologic materials to that attack. Headcut advance threshold and rate parameters were calibrated using data from field spillways that had experienced extreme flow events. The model was validated using data from additional field spillways. Results of the validation suggest that the model should provide a useful tool for current use, but that additional data and model refinement are needed.* ***Keywords.*** *Headcut, Spillway, Flood, Dam, Erosion.*

For a number of years, vegetated earth auxiliary spillways have been widely used to pass major flood flows around water control structures. This type of spillway usually consists of a trapezoidal channel constructed through natural materials, and topsoiled and vegetated as appropriate for the local area. Because of its simplicity and use of natural materials, this type of spillway often has both economic and aesthetic advantages over structural alternatives. However, the processes by which these spillways resist erosive attack are complex, and the empirical procedures available for use in design and analysis (USDA, SCS, 1956, 1973, 1985) have tended to be based on limited data. Therefore, increased concern about dam safety in recent years led the United States Department of Agriculture, Natural Resources Conservation Service (NRCS) [formerly the Soil Conservation Service (SCS)] and Agricultural Research Service (ARS) to develop a research and field data acquisition program focused on improving the understanding of the processes involved. The ultimate goals of this effort were to improve prediction of the risk of spillway breach and to develop procedures for using this improved prediction in spillway design and analysis.

Formal acquisition of vegetated earth spillway performance data began in 1983 with the formation of the SCS Emergency Spillway Flow Study Task Group (ESFSTG). This group was charged with the collection of data from SCS field spillways that experienced more than 0.9 m (3 ft) of head and/or sustained significant flow-related damage. The ESFSTG effort resulted in the compilation of data from 83 sites representing 13 flood events in 10 states. The spillway performance data included both damaged and undamaged spillways and a broad range of surface and geologic conditions. Data gathered as a result of the ESFSTG effort have been discussed in a number of publications including Ralston and Brevard (1988), Cato and Mathewson (1989), and Temple (1989).

During the time that field data were being collected by the SCS, ARS maintained a research program studying the fundamental processes related to spillway erosion, and the agencies interacted informally. In 1991, a joint SCS/ARS Design and Analysis of Earth Spillways (DAES) team was formed to utilize the information acquired in these efforts to develop new technology for use in design and analysis of these spillways. The DAES team effort was successful in developing a new spillway erosion prediction procedure (Temple et al., 1993) that has been incorporated into the NRCS design software, along with other hydraulic structure design refinements as discussed by Temple et al. (1994).

As used by the NRCS, earth auxiliary spillways are considered to perform satisfactorily if they are able to pass the freeboard hydrograph without breach. Therefore, the focus of the DAES team spillway erosion prediction model is the determination of the potential of the spillway to be breached by a given hydrograph. The model, as incorporated into the NRCS software, divides the spillway erosion process into three sequential phases for purposes of mathematical quantification. These phases are: (1) the erosion resulting in the local failure of the vegetal cover, if any, and the development of an area of flow concentration; (2) the downward and downstream erosion in the area of flow concentration leading to the formation of a vertical or near-vertical headcut (nickpoint); and (3) the upstream advance and associated deepening of the headcut with the potential of breaching the spillway. Development of the surface erosion relations used to describe the first two phases are discussed by Temple and Hanson (1994), and the conditions associated with the threshold attack required for initiation of phase 3 headcut advance are discussed by Moore et al. (1994). The basis for prediction of advance rate

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Article has been reviewed and approved for publication by the Soil & Water Div. of ASAE. Presented as ASAE Paper No. 94-2540.

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after this threshold is exceeded is presented in the remainder of this report, with the discussion of headcut advance threshold reproduced to the extent necessary to understand the advance analysis. As will be noted in later discussion, the focus on prediction of spillway breach potential made it desirable to analyze the data such that errors in the data and the model would tend to result in overprediction, rather than underprediction, of advance rate.

Spillway Performance Data

The computational model of spillway erosion incorporated into the NRCS software is a simplification of complex erosion processes. The processes associated with headcut advance are the most complex and least understood. The component of the model representing these processes is necessarily semi-empirical. Because vegetated earth spillways are normally designed with less than a 4% chance of flow in any given year, all of the field data normally must be obtained after the flood event. This means that data suitable for calibrating the headcut advance relations are expensive to obtain and difficult to interpret. Therefore, despite the comparatively long time over which the data were acquired, substantially less data are available than would be desirable.

Field Data Acquisition

Data from selected spillways that had experienced flow were gathered by SCS personnel under the direction of the ESFSTG. ESFSTG team members, accompanied by local SCS personnel, visited each site as soon as possible following the flood event. While on site, the attempt was made to determine the condition of the spillway prior to the flow event. The spillway was photographed extensively with special emphasis on damaged areas. Notes were taken describing the condition and performance of each spillway reach and factors that may have contributed to erosion damage or the lack thereof. Geologic materials exposed by the erosion were identified, mapped, and characterized according to erodibility criteria. Locations for material sampling and testing were also identified.

Because the data acquisition took place over approximately a 10-year period, and a large number of state and local personnel were involved, the quantity and quality of the follow-up data in terms of surveys and soil testing were somewhat variable. In some instances, the follow-up data were extensive; in other instances follow-up was very limited. Likewise, the quantity and quality of hydrologic data tended to be variable. Attempts were made to mark reservoir high water marks at all sites. If official rain gages or other local precipitation data were available, these were documented for use in simulating the flood flow through the reservoir and spillway. Local property owners were contacted, and data were obtained from them as available. SCS hydrologists used these data in conjunction with the DAMS2 software (USDA, SCS, 1980) to obtain a simulated outflow hydrograph for the spillway.

The data obtained from the site visits and follow-up efforts were used to develop summary reports of spillway performance for each flood. The data were also systematically compiled in computerized form for analysis such as that described herein.

Spillway Headcut Erosion Data

The data associated with headcut erosion are a subset of the overall data collected. Compilation of these data was initially approached in two different ways, with the databases developed in these approaches later merged. The first approach used was based on the observation that many of the spillways with well-defined headcut erosion had originally exited to steep natural slopes dropping to the valley floor in a short distance. For these sites, a condensed data base was developed that contained the peak discharge from the flow simulation, the drop from the end of the exit channel to the valley floor, and a description of the material (or composite of materials) judged to have dominated the interaction of the flow with the erodible boundary. Erosion was described only qualitatively. Forty-six data points were included in this data tabulation.

The second approach attempted to reproduce the behavior of individual headcuts in more detail. This required determining the time and location of headcut formation for each headcut, and identifying the location and properties of each exposed material. The relations developed for analysis of erosion phases 1 and 2 were used to determine the time of headcut development. Determination of location of headcut development was based on observation. This effectively limited the data to those sites where sudden changes in conditions such as exit to a steep slope forced relatively rapid headcut formation. This also tended to minimize the impact of any errors associated with phase 1 and 2 erosion prediction. Screening the data in this fashion resulted in identification of 33 headcuts suitable for use in analysis. Five of these headcuts experienced distinct material changes during advance, and 12 involved multiple materials in the vertical profile. Following initial screening and prior to analysis, the data associated with these headcuts were reviewed by the core DAES team members to obtain a consensus that appropriate data had been identified and that the available data had been interpreted consistently and correctly. Since confidence in the quality of the data tended to vary from site to site with the extent of observation and testing, the headcuts were assigned a subjective confidence factor from one to nine, which was included in the data tabulation.

Headcut Data Analyses

Headcut Erodibility Index

In order to analyze the data acquired from the spillways, it was first necessary to represent the properties of the geologic materials in a consistent fashion. Through preliminary data analysis, it was found that a strength-based index could be used to represent the resistance of the geologic materials to the forces generating headcut advance (Moore et al., 1994). This index approach previously has been used to characterize material for prediction of tunneling stability (Barton, 1988) and resistance to excavation (Kirsten, 1988), and shows promise for other erosion applications (Annandale and Kirsten, 1994). The form of the index adopted for use herein is essentially that presented by Kirsten (1988). This index has a range of 0.01 for noncohesive sand to values in excess of 10,000 for massive, hard rock. As applied to headcut advance analysis, the index may be computed by the relation:

$$K_h = M_s\,(RQD/J_n)\,J_s\,(J_r/J_a) \qquad (1)$$

where

- K_h = headcut erodibility index
- M_s = earth mass strength number
- RQD = rock quality designation
- J_n = joint set number
- J_s = relative ground structure number
- J_r = joint roughness number
- J_a = joint alteration number

Detailed definitions of these material parameters and procedures for their field determination are provided by Moore (1997).

Because the headcut erodibility index had not been fully developed at the time data were collected from some of the field spillways, it was necessary to estimate it from other recorded data during data compilation. The extent to which judgment was required in this estimation was reflected in the confidence number assigned, as discussed in the preceding section.

Headcut Advance Model

There is presently no generally accepted analytic model of the mechanics of headcut advance. The form of the simplified model selected was guided by preliminary analysis and the similarity of detachment by mechanical excavation and detachment by erosion. When applied to excavation, the index approach was used to predict the power required to mechanically rip the material (Kirsten, 1988). When applied to headcut erosion, the analogous parameter is the flow energy dissipation rate per unit width computed by:

$$\dot{E} = q\,\gamma\,H \qquad (2)$$

where

- $\dot{E}$ = flow energy dissipation rate (power) per unit width of headcut
- q = volumetric water discharge per unit width
- γ = unit weight of the water
- H = change in the elevation of the energy grade line through the headcut

If it is assumed that the difference in the specific energy of the flow entering and leaving the headcut is small compared with the height of the headcut, then H may be approximated as the height of the headcut.

Figure 1 is the plot obtained by applying this approach to the first data set described above, with q being the discharge per unit width of spillway and H the drop from the end of exit channel to valley floor. This plot is discussed by Moore et al. (1994) and will be reviewed only briefly here. The line drawn on figure 1 represents a lower bound of the observed damage, and is a first approximation of a headcut advance or erosion threshold line. Examination of figure 1 and the underlying data suggests the slope of the line on the log-log plot to be reasonably well established for larger values of K_h. For direct evaluation of headcuts in materials where the value of K_h approaches 0.01 (cohesionless sand), however, the threshold value would necessarily tend to zero. That is, any flow over the headcut would be capable of generating

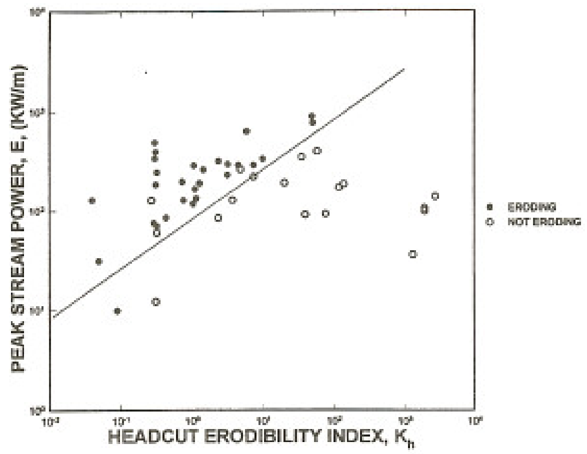

Figure 1–Headcut erodibility index vs maximum power dissipation between end of exit channel and valley floor.

erosion. Combining this logic with the fact that the use of total drop to valley floor is capable of only roughly establishing the position of the threshold line leads to a power threshold of the form (Moore et al., 1994):

$$\dot{E}_t = a\;K_h^{1/2}\,e^{\left[\frac{b}{\ln(101\,K_h)}\right]} \qquad (3)$$

where

- $\dot{E}_t$ = energy dissipation rate (power) threshold associated with headcut erosion causing upstream advance
- a & b = constants to be determined empirically

The coefficient a determines the vertical position of the threshold line on the plot, and the exponential term of the equation forces the threshold to zero for values of K_h corresponding to fine-grained non-cohesive material. The rate at which the threshold tends to zero is controlled by b.

The value of b in equation 3 is controlled primarily by the weaker materials. All observed spillway headcuts in these weaker materials experienced upstream advance. Therefore, determination of the constants of equation 3 was combined with calibration of the headcut advance rate relation. The form of the headcut advance rate relation selected for application was a simple excess attack relation analogous to the detachment rate form used in erosion phases 1 and 2 (Temple and Hanson, 1994). This relation may be written as:

$$\frac{dX}{dt} = \begin{cases} C\left(A - A_o\right) & \left(A - A_o\right) > 0 \\ 0 & \left(A - A_o\right) \le 0 \end{cases} \qquad (4)$$

where

- dX/dt = headcut advance rate in the upstream direction
- C = material-dependent advance rate coefficient
- A = the hydraulic attack
- A_o = a material-dependent threshold level of attack below which advance does not occur

Preliminary analysis by Temple (1992), which applied energy concepts to a subset of the data, indicated that the attack parameter could be expressed in the form of energy dissipation raised to a power. Accepting this approach allows the portion of equation 4 with attack above the advance threshold to be rewritten as:

$$\frac{dX}{dt} = C\left[\left(q\gamma H\right)^{a'} - \dot{E}_t^{\,a'}\right] \qquad (5)$$

where a′ is an empirically determined exponent, and the other variables are as previously defined.

During preliminary data analysis, linear, semi-log linear, and log-log linear relations were evaluated for relating the advance rate coefficient C to the headcut erodibility index K_h. The form selected for use was the semi-log linear form expressed as:

$$C = b'\ln(K_h) + d' \qquad (6)$$

subject to the limitation that:

$$C \geq c' \qquad (7)$$

where b′, c′, and d′ are all unknown constants. The limitation stated as equation 7 is a data limitation in that the maximum K_h for which advance was observed was approximately 20. Since it was the desire of the DAES team to develop a procedure that would not underestimate the rate of advance, equation 7 was introduced to prevent extrapolation of equation 6 with C decreasing with increasing K_h.

It was also noted during the preliminary data analysis that the predicted value of the exponent a′ of equation 5 tended to vary from approximately 0.25 to 0.35. Since this was generally consistent with the value of 1/3 obtained from simplified theoretical analysis (Temple, 1992), this variable was treated as fixed at 1/3 for the remaining analysis. The database was considered to be too limited, and the relations too simplified, to justify further refinement of this exponent.

The size and nature of the database combined with the desire to develop a conservative procedure also led to the decision to depart from direct statistical analysis for the determination of the unknown coefficients. Instead, an optimization approach was used with the objective of minimizing the sum of the weighted absolute value of the difference between predicted and observed headcut advance distances. The weighting factor used was the product of the previously described confidence factor and a factor that took on the value of one when the predicted advance distance was greater than the observed, and an arbitrary constant value greater than one when the predicted advance distance was less than the observed advance distance. Varying the underprediction-overprediction weighting allowed systematic headcut-by-headcut review of the predicted versus observed values until all values associated with underprediction of advance were judged to be within the potential error of the original data. This approach led to use of a weighting factor value of five for underprediction of advance. Confidence weighting factors were treated as data and were not adjusted during analysis.

The final step in preparing the data for analysis was the determination of the representative headcut erodibility index for those headcuts involving multiple materials in the vertical. Again, various schemes were tried, but it was concluded that the data were insufficient to allow empirical determination of the best approach. Therefore, the approach selected was to use the depth weighted average of the log of the index for the exposed materials. The log form of averaging was selected because of its consistency with the form taken by the index in equations 2 and 6. To avoid undue influence of surface weathering or topsoiling, up to 0.3 m (1 ft) of weaker surface material was ignored in computing the average, provided the surface material depth did not exceed 1/3 of the total headcut depth.

Results and Discussion

The extent to which the model developed in the preceding section is able to predict the observed headcut advance for the field spillways is shown in figure 2. The values of the constants obtained using the weighted optimization are:

$a = 52{,}500$ N/s $\quad = 11{,}800$ lb/s

$b = -3.23$

$a' = 0.333$

$b' = -0.0369\ \text{m-s}^{1/3}\text{N}^{-1/3}\text{h}^{-1} = -0.199\ \text{ft-s}^{1/3}\text{lb}^{-1/3}\text{h}^{-1}$

$c' = 0.0352\ \text{m-s}^{1/3}\text{N}^{-1/3}\text{h}^{-1} = 0.189\ \text{ft-s}^{1/3}\text{lb}^{-1/3}\text{h}^{-1}$

$d' = 0.142\ \text{m-s}^{1/3}\text{N}^{-1/3}\text{h}^{-1} = 0.767\ \text{ft-s}^{1/3}\text{lb}^{-1/3}\text{h}^{-1}$

The headcut advance threshold implied by the values of a and b is shown in figure 3, along with the available headcut data in the advance/no advance format.

Examination of figure 3 shows the advance threshold line to be generally consistent with the available data. The data scatter in figure 2 is greater than would be desirable. However, the point-by-point examination carried out by the

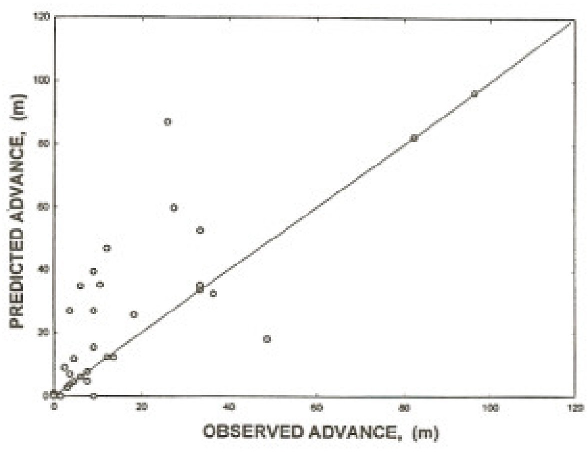

Figure 2–Predicted vs observed total headcut advance distance for field spillways.

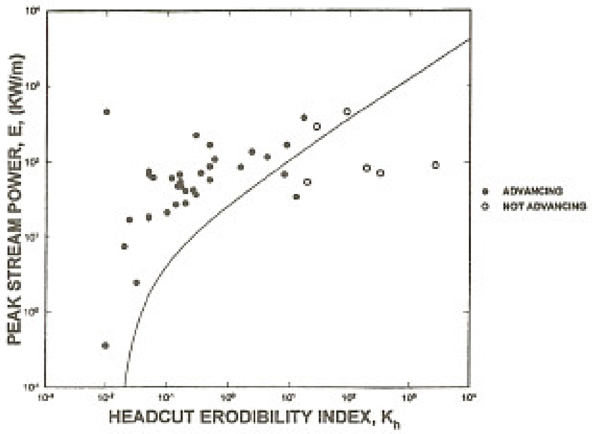

Figure 3–Headcut advance threshold in terms of power dissipation per unit of headcut width.

team found that the points generally fell within the possible interpretation and parameter estimation error of the original data on both plots. Given the complex nature of the physical processes represented by the simplified relations and the variability of the data, data scatter is to be expected. Although the departure of the predicted versus observed advance data from the line of perfect fit could have been reduced by unweighted statistical analysis, it is believed that the use of weighting as discussed to provide for subjective input by the engineers and geologists familiar with details of the sites improved the overall quality of the model for its stated purpose.

Data for validation of the headcut advance model are limited. Ten spillways were set aside for validation testing of the overall computational procedure. The predicted performance of three of these spillways was dominated by phase 3 (headcut advance erosion) action. Two of these spillways were constructed through weak sandy materials and had been breached by flood flows. The third spillway was constructed through a relatively competent limestone and shale with the constructed channel exiting to a steep hillslope. The predicted performance of these sites was judged to be generally consistent with observed performance as described below. However, the degree of conservatism (overestimation of erosion) that might be expected from the analysis described above was not apparent. The tendency for the model to be somewhat conservative was slightly more apparent in some of the other validation sites. However, the predicted erosion at these sites was also sensitive to the predicted behavior during phases 1 and 2.

The computational model predicted breach consistent with observation for the two spillways constructed through the weaker materials. Of these two spillways, the one with the most available information was the spillway previously described by Curry and Edwards (1987). This spillway was cut through a deep deposit of sandy material with a headcut erodibility index of 0.01. The crest of the spillway was 27 m (90 ft) long and was predicted to breach after slightly less than 5 hours flow. Maximum head on the spillway was computed to be about 0.6 m (2 ft). The predicted time of breach was very near the end of the outflow hydrograph that would be computed without breach. This prediction was consistent with the fact that, although breach occurred, the pool was not completely drained.

The limestone and shale spillway experienced a maximum head of approximately 2 m (6 ft) and flowed for approximately 25 h. This spillway exited to natural ground having a slope of approximately 22% with a drop of approximately 9 m (30 ft) to the valley floor. The K_h values for the interbedded material at the exit ranged from 4.0 for the weakest shale to 200 for the more competent limestone. The computed headcut advance distance was only 1.5 m (5 ft), while the maximum observed penetration of the headcut at the outlet was approximately 9 m (30 ft). For this spillway, however, determination of the headcut erodibility index for the materials actually eroded was questionable. It is possible that the near-surface eroded materials were weaker than those used to compute the values of K_h used in the computations. Therefore, it is not believed that any firm conclusions may be drawn from these results. The discussion of this site is included here to emphasize the fact that the results of applying the headcut advance relations developed herein will not necessarily result in overestimation of the erosion, and to illustrate the types of problems encountered in application of this type of model to field spillways.

Summary and Conclusions

Data acquired from field spillways over approximately a 10-year period were used to develop threshold-rate relations for use in estimating headcut erosion. The relations were developed as a part of a procedure being incorporated into NRCS structure site analysis software. The relations developed are a simplified mathematical representation of complex processes.

The similarity between excavation and headcut erosion processes led to the introduction of an index approach to representing the geologic materials for purposes of headcut advance prediction. The headcut erodibility index is capable of representing materials from cohesionless sand to competent rock on a continuous scale. It is determined from the material properties that govern the material's resistance to surface detachment and mass failure. Procedures for field determination of the headcut erodibility index are described by Moore (1997).

The extent to which subjective evaluation entered into the development of the headcut advance relations has been emphasized in this report. This was done to make clear the fact that prediction of this type of erosion is currently less than an exact science and should be approached accordingly. In developing the relations, the attempt was made to generate a procedure in which errors associated with process simplification would lead to overestimation rather than underestimation of the extent of erosion. However, it is intended that the headcut advance predicted by these relations be treated as a best estimate rather than a maximum. The limited data available for validation of the resulting computational procedure are consistent with this treatment.

Because headcut erosion processes are complex and the headcut erodibility index approach is relatively new, potential exists for refinement of the estimates of headcut threshold and advance rate through continued research and field data collection. Data are most lacking for conditions involving high discharges and erosion-resistant geologic materials. The relations presented may be used to provide a best estimate of headcut behavior until additional data allows the development of more refined relations.

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