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Bureau of Reclamation use of Erosion-Modeling Innovations from ARS-Stillwater

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Abstract. *The Bureau of Reclamation has enjoyed a profitable partnership with the USDA's Hydraulic Engineering Research Unit at Stillwater, Oklahoma, collaborating on and benefitting from research related to erosion of cohesive soils and headcut development affecting earthen spillways, embankment dams, and canal embankments. This paper provides an overview of our organizations' shared interests, highlights key areas of collaboration, and illustrates beneficial applications of USDA-developed technologies to Reclamation projects. Future research needs in Reclamation and potential areas for continued collaboration are also discussed.*

Keywords. *Erosion, erodibility, embankments, dams, spillways, hydraulic modeling, dam breach, overtopping protection, riprap*

Introduction

The Bureau of Reclamation Hydraulics Laboratory at Denver, Colorado was established in 1947 at the former site of the World War II-era Remington Arms munitions factory. Since 1930 Reclamation had operated hydraulic modeling facilities at several locations (Fort Collins, CO; Montrose, CO; Hoover Dam; Grand Coulee Dam; downtown Denver). The laboratory operations at Fort Collins were a joint venture with USDA, involving Reclamation staff utilizing facilities initially established by USDA under the direction of Ralph Parshall (Burgi 2002).

The focus of Reclamation's laboratory has typically been broad, but a central theme has always been assuring safety and stability of dams and their appurtenances, the backbone of Reclamation's infrastructure that supports irrigation of arid lands in the west. The USDA Agricultural Research Service (ARS) established the hydraulics laboratory at Stillwater, Oklahoma in 1940 with a focused initial charge to develop criteria for design of grassed waterways for erosion control and soil stabilization on agricultural lands nationwide. In recent decades the USDA's large dam and reservoir infrastructure (assistance with construction of over 11,000 dams) has become a greater focus of the Stillwater laboratory, while Reclamation has continued to study risks associated with its inventory of more than 300 large dams and over 8,000 miles of irrigation canals. The similarity of these objectives has led to many opportunities for fruitful collaboration between the two laboratories.

Erosion of Cohesive Soils

The erosion of cohesive soils is a fundamental physical process affecting the performance of earthen spillway channels and the stability of embankment dams and canal embankments. The USDA's interest began with their studies that developed design criteria for grassed waterways, since cohesive soils often provided the rooting foundation for the grass erosion protection system, and the erosion of underlying cohesive soils could lead to vegetation failure. Studies to develop design criteria that limit erosion eventually led to studies to evaluate the damage done when erosion cannot be prevented. This eventually produced computer models (DAMS2 and SITES) for simulating headcut development in the cohesive soils encountered in the earthen spillway channels typically provided on USDA dams.

In the mid 1990's both agencies were making efforts to develop and improve capability for modeling breach processes affecting embankment dams. USDA was feeling the effects of increasing urbanization around its dams. Reclamation was experiencing similar changes, and in addition to its responsibility for safety of its own dams, it was also the lead dam safety agency for many dams owned by other Department of the Interior agencies. Examination of dam failure case studies revealed that headcutting processes similar to those observed in earthen spillways also seemed to dominate in most dam failures, especially when soils were obviously cohesive. This led to collaboration between the two laboratories, including joint involvement in two workshops on the subject of dam breach modeling, the first held at the Stillwater laboratory in 1998, and the second in Oklahoma City in 2001. Key topics of interest to Reclamation and other attendees at those workshops were ARS's large-scale dam breach experiments and the accompanying submerged jet erosion test device that had been developed at Stillwater to characterize erodibility of cohesive soils using numerical parameters that could be directly applied to modeling purposes.

Shortly after the 2001 workshop, Reclamation began to be involved in a separate effort to improve embankment dam breach models organized through the CEATI-DSIG (Centre for Energy Advancement through Technological Innovation-Dam Safety Interest Group). This international collaboration of electric power producers collectively supports research topics of interest using funding from member organizations as well as in-kind contributions of research expertise. A working group was formed with representatives from Electricite de France (EdF), Hydro Quebec, Manitoba Hydro, Ontario Power Generation, Elforsk (Sweden), the U.S. Army Corps of Engineers (USACE), and Reclamation. The author was asked to coordinate the working group's activities and one of my first actions was to actively seek input from Greg Hanson and Darrel Temple of the Stillwater laboratory. Despite the fact that ARS was not a member of the DSIG, both became regular contributors and central resources to the DSIG working group as the value of their ongoing experimental and model development work was plainly evident.

A parallel development at Reclamation in the early 2000's was the development of the Hole Erosion Test and Slot Erosion Test devices through a collaboration of Reclamation's soil mechanics laboratory and Dr. Robin Fell and Dr. C.F. Wan of the University of New South Wales. Jeff Farrar of Reclamation was a primary contact with the UNSW group and also was aware of Dr. Hanson's submerged jet test. Mr. Farrar got the author involved in Reclamation's efforts to create a more reliable HET capability, but also urged that Reclamation should add the submerged jet test capability to its arsenal of erosion modeling tools. In early 2006 Reclamation constructed its first submerged jet erosion test device, using plans provided by Dr. Hanson. The initial purpose for building the device was to carry out a comparative evaluation of the jet and HET devices to determine whether they provided comparable results when applied to the same soils. The author completed this study with the aid of Pierre-Louis Regazzoni, a Ph. D. student from France who was funded by EdF to spend 9 months working in the U.S. laboratories of Reclamation, USACE, and ARS. The study demonstrated significant differences in the test results when the HET and jet test were applied to similar soils and showed that the jet test was the preferable device due to its robustness and ability to characterize soils over a wider range of erodibility characteristics.

In 2008 the DSIG group embarked on an effort to carry out controlled evaluations of ARS's SIMBA (SIMplified Breach Analysis) model (predecessor to WinDAM), and HR-BREACH developed at HR Wallingford. This brought into the group Dr. Mark Morris representing Wallingford (also not a DSIG member), who had attended the 1998 and 2001 breach workshops in Oklahoma.

Also in January 2008, Reclamation experienced the significant failure of a canal embankment on the Truckee Canal near Fernley, Nevada. Occurring less than 2½ years after the failure of levees in the New Orleans area during hurricane Katrina (August 2005), this event heightened Reclamation's awareness of the risks posed by its network of more than 8,000 miles of irrigation canals. Most of these canals were originally constructed in lightly populated rural areas, but a century of development in the west had led to urbanization around some canals which created new risks, similar to the increase of hazards posed by USDA watershed dams in urbanizing areas. This prompted Reclamation to undertake a series of physical model tests to study breach mechanisms of canal embankments. The testing was patterned closely after the dam breach experiments that had begun about a decade earlier at the Stillwater lab. Submerged jet testing was used to characterize embankment soils and the erodibility of the embankments was regulated by controlling compaction procedures with the benefit of concepts illustrated by Hanson and Hunt (2007). The tests showed that breach processes were similar to those observed in embankment dams and the collected data confirmed relations developed by Hanson et al. (2011) and Hunt et al. (2005) between soil erodibility, applied stress, and observed erosion rates. With the benefit of additional numerical modeling, this study led to the development of a comprehensive procedure for making appraisal-level estimates of canal breach outflow hydrographs (Wahl et al. 2012). Today, Reclamation is continuing to carry out physical model tests in its laboratory with the objective of improving our understanding of erosion and breach processes for embankments that differ from the homogeneous and cohesive soil configurations that have been extensively studied in recent years.

Recent Applications

Some recent applications of the SITES and WinDAM B models on Reclamation projects will be briefly discussed.

Terminal Reservoir

Terminal Reservoir (Wahl 2013) is a small impoundment (about 100 ac-ft) constructed in 1959 at the termination of the Putah South Canal near Fairfield, CA. The reservoir is formed by two small homogeneous compacted embankments, each about 24 feet high containing clay soils with plasticity index (PI) values ranging from about 16 to 32, averaging about 20. The reservoir is filled by a regulated canal; only a small natural watershed drains into the reservoir. Residential housing developments are located just downstream from both embankments.

The primary potential failure mode for the reservoir is triggered by transverse cracking through the embankments during a seismic event. This would lead to flow through the crack, development of a headcut, and eventually the migration of that headcut through the embankment. Initial estimates of breach outflow made using established regression equations (e.g, Froehlich 1995a; 1995b) predicted peak outflows and times of failure that were expected to lead to loss of life below the dam. Reclamation began a corrective action process to consider modifications to the structure, such as the addition of a toe berm.

The relatively small size of the reservoir and potential erosion resistance of the embankments prompted Reclamation to do more detailed modeling of the failure of this dam. In March 2013 the author made a site visit to the reservoir and carried out six jet erosion tests over a two day period with the aid of local project personnel. The tests were conducted on the downstream sides of the embankments and on the crest of one embankment, with test surfaces exposed by careful excavation with hand tools. The results of the six tests suggested that the erosion rate coefficient, k_d, ranged from 0.1 to 2.5 ft/hr/psf, and the critical shear stress, τ_c, was between 0.001 and 0.1 psf. These values were consistent with those expected based on knowledge of other soil properties and the construction history of the embankments.

Following the site visit a series of WinDAM B model simulations was conducted using the range of measured erodibility parameters and estimates of other soil properties based on knowledge of the soils. The simulations showed that the time needed for a headcut to advance through the embankment was quite long, about 8 hours using best estimate soil parameters and 3-6 hours using projected worst-case values. This, combined with the small size of the reservoir meant that significant drawdown would occur before the breach was initiated, leading to a much smaller breach outflow than predicted using traditional breach parameter and peak outflow regression equations. Because the potential failure mode was flow through a transverse crack rather than overtopping, judgment was required to apply WinDAM B to this case. Flow through the crack was simulated like flow through a narrow pilot channel and a range of initial crack widths and depths was investigated, some wide enough that for practical purposes they would be best described as pilot channels. These sensitivity tests showed that peak breach outflow diminished as the crack width was increased because there was more reservoir drawdown prior to breach initiation. Peak breach outflow increased up to a point with greater initial crack depth, then diminished; the depth that caused peak outflow was used to estimate the worst possible outcome.

The WinDAM B breach outflow hydrographs were provided to the analysis team that estimated consequences of dam failure. The long breach initiation time which would provide opportunity for warning and evacuation of downstream residents was a significant factor leading to a conclusion that the dam should not be classified as High Hazard. The Corrective Action study concluded that the dam did not need to be modified. This result could not have been justified without the in situ submerged jet erosion tests and the use of the WinDAM B model.

Willow Creek Dam

Willow Creek Reservoir is a 32,230 ac-ft storage reservoir located about 70 miles north of Helena, MT on Willow Creek, a tributary to the Sun River. An uncontrolled emergency spillway cut through glacial till soils has been the subject of repeated investigations to determine whether it may breach during large floods, and if so whether it has the potential to cause loss of life in downstream areas. Reclamation is presently attempting to use both the SITES and WinDAM B models to analyze this spillway erosion problem. Soil erodibility parameters have been estimated initially based on limited information obtained from 1997-era test pits and drill holes. The SITES model is being used to estimate whether breach can occur, and WinDAM B has been used to make estimates of the potential breach outflow hydrograph, treating the spillway channel like an embankment dam having very flat upstream and downstream slopes. A small concrete sill is the only control structure at the site, but it is being neglected in the analysis since it is expected that if erosion does occur through the spillway it will be deep enough to undermine the structure. Drilling operations are currently underway to attempt to recover relatively undisturbed samples for laboratory analysis and possible jet testing. The potential presence of gravel in these samples will be a complicating factor. To address this issue, Reclamation has recently completed a small research investigation that considered methods for applying the submerged jet test to cohesive soils containing significant amounts of gravel (Wahl 2014).

Research Needs

Although the collaboration of the Reclamation and ARS-Stillwater labs has led to many improvements in rock and soil erosion modeling, erosion of embankments and earthen spillways continues to be a very difficult problem for Reclamation and other agencies. The problems are especially difficult when materials tend toward the rock end of that spectrum. Some key issues are highlighted below.

- For intact rock, k_d values cannot be effectively measured with the jet test but would seem intuitively to be low. However, without a method to measure k_d in these materials, it is difficult to justify the use of low k_d values in SITES.
- For loose rock of gravel size or larger, k_d values again cannot be measured, but there is great temptation on the part of modelers to apply WinDAM or similar models to embankments that might contain either clean coarse grained materials or dirty coarse-grained materials (i.e., a mixture of cohesive and non-cohesive soils). There would be significant value in measuring erosion rates of these materials and relating them to the erosion rates that can be measured for cohesive soils using the submerged jet test.
- There is a fundamental need to establish means of identifying the threshold between headcut erosion behavior and surface erosion behavior on the basis of soil properties, channel configuration, or other factors.

The WinDAM embankment erosion model benefited greatly from technologies that accompanied the development of the SITES spillway erosion model. Now, it seems there may be opportunities for SITES to benefit from new concepts that have come out of the WinDAM development effort.

SITES provides capabilities for modeling headcut erosion in spillway channels as a function of applied hydraulic stress and soil erodibility parameters. (The same models are also in the spillway erosion component of WinDAM). Specifically, SITES models two modes of erosion: (1) deepening and headcut development, and (2) headcut advance. The first mode of erosion is related to the soil detachment rate coefficient, k_d, which is well-defined for soils and can be measured using the submerged jet erosion test. However, this parameter is undefined for rocky materials, especially semi-intact rock masses that derive significant erosion resistance from the interconnection of individual particles into a continuous rock mass. Headcut advance is related to the headcut erodibility index which can be determined with reasonable accuracy for both soils and a wide range of rock materials (including intact rock). USDA's guidance for applying SITES to rocky materials suggests the use of very conservative values of k_d (indicative of loose rubble rather than intact rock) that yield rapid deepening and gully development, which seems unreasonable for intact rock. This allows headcut heights to quickly become extraordinary in model runs, eventually leading to headcut advance due to extreme drop heights, ***even when the headcut index of the rock might be large***. There is a great need for relating rates of headcut deepening and erosion development to parameters that can be readily evaluated for rock-like materials, such as the headcut erodibility index.

The WinDAM embankment breach model uses methods for modeling deepening and headcut development that are similar to the methods in SITES. However, the WinDAM dam breach model also introduced new methods for modeling headcut advance for soils in embankment dams. An energy-based model predicts headcut advance as a function of energy dissipation rate and a headcut advance coefficient, C. The value of C has been correlated with values of k_d (Hanson et al. 2011). A second stress-based model predicts headcut advance rates as a function of applied stress, critical shear stress of the soil, and undrained shear strength (no k_d value needed). Note that neither of these models requires estimation of the headcut erodibility index, so when applying SITES to spillway erosion problems involving only soil-like materials, it could be helpful if the SITES model offered the new WinDAM headcut advance models as an option.

The SITES model (and the WinDAM spillway erosion model) cannot simulate the actual breach enlargement process for a spillway breach. (The simulation stops when breach initiates). Estimating the spillway breach outflow hydrograph is the next request whenever a spillway breach is expected. Developing this capability in SITES would be a valuable improvement.

WinDAM's dam breach modeling capability only supports overtopping erosion of homogeneous embankments at this time, although internal erosion capabilities are due to be released soon and there are long-term plans to add ability to model zoned embankments. For Bureau of Reclamation use, the ability to model zoned embankments would be very valuable, since most of our large embankment dams utilize zoned construction.

Conclusion or Summary

The USDA and Bureau of Reclamation hydraulics laboratories have enjoyed a long history of collaboration on soil and rock erosion research and the Bureau of Reclamation has benefited significantly from technologies developed by the Stillwater lab, both for our own ongoing research and for our dam safety management efforts.

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