Experimental Methods for Studying Canal Breach Processes

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ABSTRACT

Small-scale physical hydraulic models were constructed and tested to failure to study the breaching processes of typical irrigation canal embankments. The tests considered effects of varying material properties and different failure initiation conditions. Submerged jet erosion tests were performed during embankment construction and following each breach test to evaluate soil erodibility. This paper describes the test facilities, instrumentation, and methods used to artificially control model boundary conditions to effectively simulate the behavior of a long canal reach within a relatively small laboratory area. Numerical modeling was also used to study the dynamic response of a canal to a breach event, free from the physical constraints of the laboratory facility.

INTRODUCTION

The Bureau of Reclamation has constructed more than 8,000 miles of irrigation water delivery canals since 1902. Although typically reliable, canal failures have occurred on occasion throughout Reclamation's history. Threats to canals include animal burrows, tree roots, embankment and foundation issues, pipe penetrations, seismic events, internal erosion under static loading, hydrologic events, and operational incidents. Canal failures can have significant consequences, and potential consequences are increasing as urban development occurs near formerly rural canals.

To understand the risks associated with individual canals, modeling of potential failures is needed. Tools for predicting peak outflow from traditional embankment dams do not account for the hydraulic boundary conditions upstream from the breach that are imposed by a canal of finite cross section and volume. The capacity of a canal to convey water to the site of a breach limits the potential peak outflow.

To gain a better understanding of canal breach processes and develop guidance and tools for evaluating flooding risks associated with potential canal breaches, Reclamation has performed scale model canal breach tests in its hydraulics laboratory and conducted numerical modeling to study the interaction between the rate of breach development and the transient hydraulic behavior of an extended canal reach (Wahl and Lentz 2010). This paper describes the experimental methods applied in this research project.

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CANAL BREACH OUTFLOW CONSTRAINTS

Outflow hydrographs from breached canals differ from traditional dam breach outflow hydrographs because the water volume upstream from the breach is more limited and the conveyance capacity of the canal constrains the supply of water to the breach site, hence limiting the maximum outflow. Dun (2007) provided the most notable study of the hydraulics of a canal breach in a study of the Llangollen navigation canal, which failed in the United Kingdom in 2004. Dun created a numerical model that simulated flow through the breach with a critical-flow section sized to match the observed breach dimensions. Breach flow was also limited by two additional critical-flow sections in the upstream and downstream reaches of the canal, with reverse-flow in the downstream reach. Dun described two stages of breach development, an early stage in which the outflow is limited by the breach geometry, and a later stage during which the breach has become large enough that discharge is then limited by canal capacity. In some cases, only the first phase occurs, depending on the rate and extent of breach development, the speed of operational response by canal operators, and the volume of water contained in the canal reach.

The situation of greatest concern for canal operators is the case of a rapid breach that develops into the second stage before canal operators are able to begin shutting down the canal, and before the canal water level has dropped significantly. To represent this worst-case condition, we designed the laboratory test facility so that a nearly constant upstream water level could be maintained in the canal. This is representative of a breach developing rapidly within a long canal reach.

TEST FACILITY

Figure 1 shows a photo and Figure 2 a plan view of the physical model test facility, which consists of a 70-ft long trapezoidal canal constructed between twin head boxes, one at each end of the canal. The canal has nonerodible plywood walls along most of its length, with one sidewall missing in a 20-ft long embankment test section midway between the two head boxes. Flow can be supplied into each end of the model and flow can also be released into wasteways through gates located in each head box. The flow capacity into each head box is equal to the maximum theoretical critical-depth flow that can be produced in each canal reach following a hypothetical instantaneous and total failure of the test embankment. The gate in the downstream head box is oversized so that it can release the entire critical-depth flow plus the normal-depth discharge of the canal. This allows tests to be conducted with normal canal flow initially occurring past the test section. As a breach develops, the head box waste gates are throttled to keep more of the model inflow in the canal, thus providing additional flow toward the developing breach and maintaining near-normal canal water depths, simulating the slow draining of an extended-length canal reach. By accomplishing this flow change using gates, no manipulation of the output from the laboratory pumps is needed during a test. The typical procedure used was to throttle the waste gate in the upstream head box first until canal water levels began to drop, then to throttle the downstream waste gate to maintain canal water levels as long as possible. This maintains normal flow past the breach site for the longest

possible time. The canal and embankment cross-section used for the facility is shown in Figure 3. The model canal was constructed with no slope over the short reach of the model. Flow measuring flumes in each wasteway and measurement of the inflow to each end of the model make it possible to compute the outflow through the canal breach.

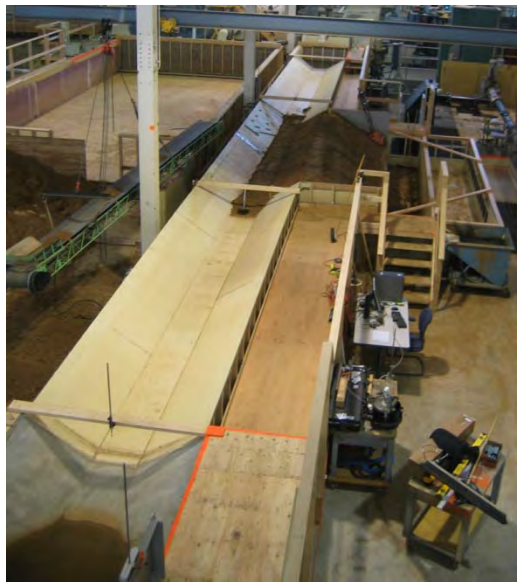

Figure 1. — Canal breach model test facility viewed from downstream end. Initial flow in the canal is toward the viewer. The erodible embankment section is at the right side.

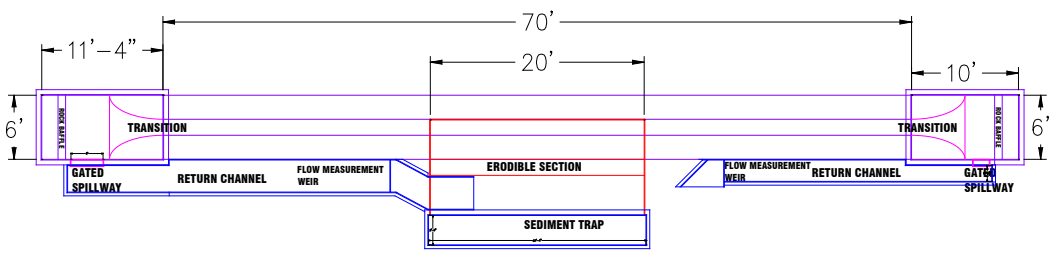

Figure 2. — Plan view of canal breach model test facility. Flow enters via the head boxes at each end of the model.

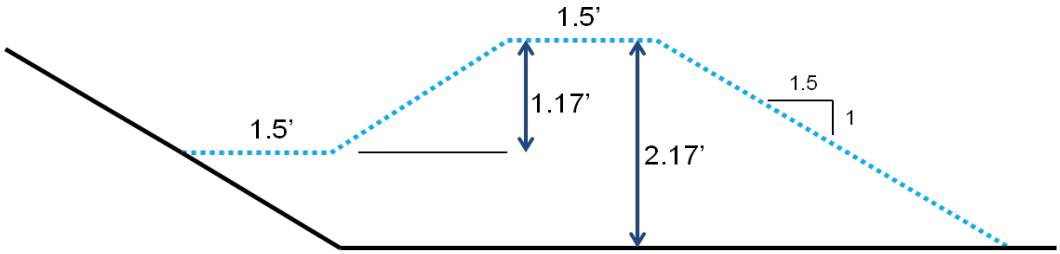

Figure 3. — Cross-section view of model canal and embankment test section.

The tested embankments were constructed in the model as simulated fill sections in a canal reach that is elevated above the surrounding landscape. On the wetted side of the embankment, the embankment crests were constructed to an elevation of 1.17 ft above the canal invert. On the land side of the embankment, the toe of the embankment was located 1.0 ft below the canal invert elevation. In the model, embankment material was placed in the invert of the canal to allow for potential downward erosion in this zone, and advancement of headcuts up both canal reaches away from the breach. This configuration was not a model of any specific situation in Reclamation, but was meant to be representative of canals constructed as fill sections, a configuration that is recognized to carry heightened risk of failure and potential for damage to surrounding areas.

The decision to not include a canal lining material was based on the fact that embankment breach typically takes place by headcutting, which progresses from the downstream side of the embankment toward the upstream side (toward the canal prism). Whether the driving force for erosion is an overtopping flow or piping flow through an existing flaw in the canal lining and embankment, failure takes place by erosion of embankment materials due to this flow. The lining simply collapses after the embankment has been eroded and all structural support for the lining is gone. The effect of the lining upon the critical erosion processes is minimal.

BREACH TESTS

Three embankment breach tests have been conducted thus far. All three embankments were constructed as homogeneous sections using the same soil, a silty sand with low plasticity (PI=5). Different levels of compaction effort and different water contents during compaction were used for each embankment so the erodibility of the finished product varied dramatically, even though the same soil material was used.

Table 1. — Soil characterization.

Classification[a]	Grain size[b]			Plasticity Index, PI[c]	Standard Proctor Compaction[d]	
	% gravel	% sand	% fines		$\gamma_{d,max}$, lb/ft^3	w.c.$_{opt}$
SM – silty sand	6	69	25 (10% < 0.005 mm) (8% < 0.002 mm)	5	120.9	12%

Standards used to determine soil properties:
[a] ASTM D2487, USBR 5000; [b] ASTM D2487, USBR 5330; [c] ASTM D4318, USBR 5360; [d] ASTM D698A.

Prior to embankment construction the soil was characterized through gradation analysis, compaction testing, and a series of laboratory submerged jet tests (ASTM D5852; Hanson and Cook 2004; Hanson and Hunt 2007). Sand cone density tests were performed during embankment construction, and submerged jet tests were also performed in situ during embankment construction and following each breach test. These tests yielded estimates of the critical shear stress and detachment rate coefficient for each compacted embankment. The tests showed that detachment rate coefficients varied by almost 3 orders of magnitude for the tested embankments.

The three tests performed thus far all utilized internal erosion or piping as the failure initiation mechanism. A #4 rebar embedded in each embankment during construction was pulled out to create a pre-formed pipe through the embankment. Flow through this pipe then produced the canal breach. In the first two tests the pipe was located deep in the embankment, at about the elevation of the canal invert. In the third test the pipe was located high in the embankment, just below the normal canal water surface elevation. Erosion resistance of the first embankment was very high, so a pilot channel was eventually cut through this embankment and the test was converted to a case of failure by overtopping erosion.

The three tests produced three widely varying breach development scenarios. Initiation of breach and enlargement of the breach opening were very slow in the first test, with the breach never enlarging enough to reach Dun's second stage, even after 21 hours of operation. In the second test the embankment was so erodible that the initiation and complete development of the breach took less than 7 minutes. In the third test, breach initiation (enlargement of the pipe and progression of the initial headcut through the embankment) took about 4.75 hours because head on the pre-formed pipe was small and the flow rate available to cause erosion was low. Once breach initiation was completed, enlargement of the breach to the point that peak outflow occurred required only an additional 4 minutes.

During each of the tests, physical measurements and photographic and video records were collected that enabled estimation of key erosion rates, such as the rates of upstream headcut advance and the rates of breach widening. These data have been compared to similar data collected from traditional embankment dam breach testing (Hanson et al. 2005; Hunt et al. 2005), and the relationships between soil erodibility parameters, applied stress, and observed erosion rate have been consistent in both situations.

NUMERICAL MODELING

The physical model facility was designed to simulate worst-case boundary conditions for erosion and breach development (a near-steady water surface in the canal during breach initiation and enlargement). The physical model could not simulate the dynamics of transient flow in a lengthy canal. To overcome this limitation, numerical unsteady-flow simulations have since been used to determine how breach outflow hydrographs would vary, given prescribed breach erosion rates and considering the interaction of canal transients and the rate of breach development (Wahl 2012).

CONCLUSIONS

The physical model studies described here and subsequent numerical modeling have led to the development of appraisal-level procedures for estimating the peak outflow rate and other breach outflow hydrograph characteristics as a function of canal hydraulic properties, breach development rate, the length of the affected canal reach, and the location of the breach relative to upstream and downstream check structures. These procedures will help water managers identify canal reaches that have potential to produce large peak outflow rates.

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