The National Dam Safety Program

Final Report on Coordination and Cooperation with the European Union on Embankment Failure Analysis

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REPORT

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1. INTRODUCTION

1.1 Overview

The US Dam Safety community has similar needs and activities to those of the European (EU) Dam Safety community. There has been an emphasis in the EU community on investigation of extreme flood processes and the uncertainties related to these processes. The purpose of this project was to cooperate with the organizations involved in these investigations over a three year period. The purpose of this cooperation was to: 1) coordinate US and EU efforts and collect information necessary to integrate data and knowledge with US activities and interests related to embankment overtopping and failure analysis, 2) Utilize the data obtained by both groups to improve embankment failure analysis methods, and 3) provide dissemination of these activities and their results to the US dam safety community. Dissemination was to be accomplished by:

1) Conducting a special workshop at a professional society meeting involving invited speakers from Europe and the United States. This session was held as a one day workshop at the Annual Conference of the Association of State Dam Safety Officials 2004 Dam Safety. The title of the day long workshop was; "Workshop on International Progress in Dam Breach Evaluation." Ten presentations were included in the workshop (see appendix for manuscripts).

2) A final report integrating EU and US research findings and results related to earthen embankment overtopping failure over the 3-year period would be developing and reporting in the form of a FEMA/USDA document. This report is included in the following pages.

1.2 Background

Sending U.S. representatives to cooperate with EU was included in the research needs identified by participants in the FEMA, "Workshop on Issues, Resolutions, and Research Needs Related to Embankment Dam Failure Analysis," held June 26-28th, 2001, in Oklahoma City, OK. The prioritized list of fourteen research needs, taken from the proceedings of this workshop (USDA, 2001), is shown in table 1. This list was based on an aggregate score of votes by the workshop participants on value, cost, and probability of success of the specified research needs. Topic number 13 (No. 7 priority ranking) of the research list, cooperation with EU dam failure analysis activities, contributes to addressing topic numbers 4, 5, 7, 10, 11, and 12, with priority rankings of 10, 3, 5, 13, 11, and 2 respectively.

Both the US and EU have had research activities related to prediction of performance of earth embankment dams during extreme flood events. These projects including; the EU Concerted Action on Dambreak Modeling (CADAM) project, Investigation of Extreme Flood Processes and Uncertainty (IMPACT), Integrated Flood Risk Analysis and Management Methodologies (FLOODsite) (Morris et al., 2004), and the work of USDA-

Agricultural Research Service to address overtopping of aging dams were summarized in the workshop proceedings (USDA, 2001). These projects are seen to have a number of complimentary concerns and goals. Within these projects there has been a component of research focused on erosion mechanics of overtopped earthen embankments including physical and numerical modeling. This report focuses on the effort of both groups in this area and on integrating these findings.

TABLE 1 – RESEARCH TOPICS RANKED BY AGGREGATE SCORE

TOPIC NUMBER	RESEARCH / DEVELOPMENT TOPIC(S)	AGGREGATE SCORE	RANK
2	Develop forensic guidelines and standards for dam safety experts to use when reporting dam failures or dam incidents. Create a forensic team that would be able to collect and disseminate valuable forensic data.	54	1
12	Using physical research data, develop guidance for the selection of breach parameters used during breach modeling.	52	2
5	Perform basic physical research to model different dam parameters such as soil properties, scaling effects, etc. with the intent to verify the ability to model actual dam failure characteristics and extend dam failure knowledge using scale models.	40	3
1	Update, Revise, and Disseminate the historic data set / database. The data set should include failure information, flood information, and embankment properties.	38	4
7	Develop better computer-based predictive models. Preferably build upon existing technology rather than developing new software.	34	5
9	Make available hands-on end-user training for breach and flood routing modeling that is available to government agencies and regulators, public entities (such as dam owners), and private consultants.	30	6
13	Send U.S. representatives to cooperate with EU dam failure analysis activities.	30	7
3	Record an expert-level video of Danny Fread along the lines of the ICODS videos from Jim Mitchell, Don Deer, etc.	29	8
6	Update the regression equations used to develop the input data used in dam breach and flood routing models.	20	9
4	Identify critical parameters for different types of failure modes	14	10
11	Develop a method to combine deterministic and probabilistic dam failure analyses including the probability of occurrence and probable breach location.	10	11
14	Lobby the NSF to fund basic dam failure research.	4	12
10	Validate and test existing dam breach and flood routing models using available dam failure information.	2	13
8	Develop a process that would be able to integrate dam breach and flood routing information into an early warning system.	0	14

2.0 RESEARCH ON EROSION MECHANICS OF OVERTOPPED EMBANKMENT

2.1 Review

Interest in the occurrence and effects of overtopping flows on earth embankments has existed for years. Dam overtopping is often sited as one of the principal causes of dam failure for earthen embankment dams (Singh, 1996). Based on conclusions made by Ralston (1987) there are about 57,000 dams on the USA national dam inventory that have the potential for overtopping. This is not only a USA problem but is an International problem as well. Reservoirs overtop as a result of inflow exceeding the capacity of the reservoir storage and spillway outflow system, and since this risk can never be completely eliminated, the challenge is determining in advance how these embankments will perform. The hazard to people and property from earth dam breach is increased by the suddenness of the flood and difficulty in predicting the dam failure. Predicting the severity of flooding downstream of a dam failure is not only dependent on the size of the reservoir, and size and shape of the breach that forms (Froehlich, 1995), but is also dependent on the rate of breach formation (Walder and O'Connor, 1997) which in turn relates to the design of embankment condition and materials used. Unfortunately, there is little data available from historical cases on amount and rate of erosion, breach dimensions, and discharge as a function of time during a dam overtopping event. Typically, the data that do exist are limited to post-event information: final depth, breach width, shape, and eroded volume; and estimated peak discharge, overtopping depth, and failure time (Wahl, 1998). Breach parameter prediction equations based on statistical analysis of this post-event information have been developed (SCS, 1981; MacDonald and Langringe–Monopolis, 1984; Costa, 1985; Froehlich, 1987 and 1995; Walder and O'Connor, 1997; and Wahl, 1998) but they have significant uncertainty and are logically influenced by the nature of the embankment materials used in the underlying datasets. Failure time, as an example, is especially difficult to predict with uncertainty approaching ±1 order of magnitude (Wahl, 2001). In addition to the uncertainty issue, the breach parameter prediction equations and numerical models that have been developed do not adequately address the breach erosion process, the rate of breach failure, or the influence of embankment vegetation, materials, and geometry.

Due to these shortcomings in the existing knowledge base, recent research studies on embankment overtopping and failure have been conducted in the United Kingdom (UK), Norway (N) and the United States (US). HR Wallingford of the UK has conducted 22 small-scale laboratory embankment-overtopping tests as part of the European Commission funded project, IMPACT. Seven of these tests were conducted on cohesive materials. Large-scale field tests of seven embankments were tested in Norway in the period of 2001-2003. One of the tests in Norway was conducted on a cohesive embankment. The Agricultural Research Service (ARS) of the US Department of Agriculture (USDA) has conducted: 1) overflow tests on steep vegetated and bare channels; 2) large-scale headcut migration flume tests; 3) large-scale embankment overtopping tests; and 4) breach widening tests.

This report provides a summary of research activity focusing on overtopped cohesive earth embankment tests in the UK, Norway, and the US. It is hoped that the data from these research activities can: 1) establish a better understanding of the embankment breaching processes; 2) determine the rate of breach of cohesive embankments; 3) provide data for numerical model validation, calibration and testing, and hence improve modeling tool performance; and 4) provide information and data to assess the scaling effect between field and laboratory experiments.

2.2 Description of Field and Laboratory Research Tests

The entities conducting the embankment breach research described herein each have unique facilities, expertise, and perspective on the problems to be addressed. The studies conducted are briefly described below.

2.2.1 Small-scale laboratory tests of breach formation – UK

A total of 22 laboratory experiments were undertaken at HR Wallingford in the UK (Hassan et al., 2004). The overall objective of these tests was to better understand the breach processes in embankments failed by overtopping or internal erosion and identify the important parameters that influence these processes:

2.2.1.4 Series #1 – 0.5 m Small scale embankment overtopping tests.

Nine tests were conducted on homogeneous non-cohesive 0.5-m high by 6-m long embankments. Each embankment was constructed from non-cohesive material, with more than one grading of sand used along with different embankment geometries, breach locations, and seepage rates. The three gradings used in testing were: 1) uniform coarse grading with a D_{50} of 0.70-0.90 mm; 2) uniform fine grading with D_{50} = 0.25 mm; and 3) wide grading with a D_{50}=0.25 mm.

2.2.1.5 Series #2 – 0.6 m Small scale embankment overtopping tests.

Eight tests were conducted on homogeneous cohesive 0.6-m high by 4-m long embankments (Figure 1). Seven embankments were constructed from a cohesive soil material having a D_{50} = 0.005 mm with 43% clay and one embankment was built from a moraine material with D_{50} = 0.715 mm with 10% fines. The seven cohesive embankments were constructed using two different compaction efforts and various water contents. One compaction effort was half the other based on the number of drops of a hand-tamping tool. The compaction water content ranged from 19 to 28% for the seven tests. The resulting compaction densities ranged from 1.13 to 1.23 g/cm^3. The physical modeling set-up and results including; inflow, outflow, and reservoir water surface elevations for one of the cohesive embankment overtopping breach tests are shown in Figures 1 and 2.

2.2.1.6 Series #3 – Small scale internal erosion tests.

Five tests on homogeneous moraine and actual river embankment materials were conducted to assess mechanisms and dimensions associated with the initiation of internal erosion.

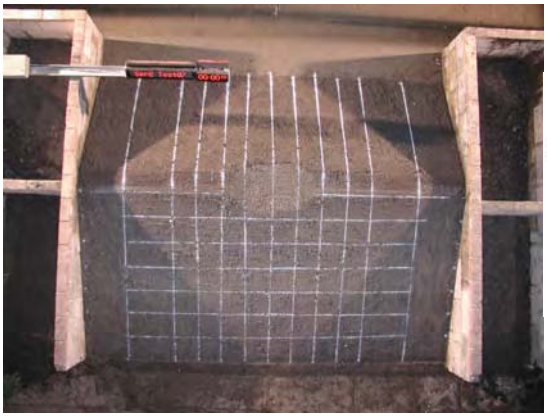

Figure 1. Embankment overtopping setup at HR Wallingford, UK.

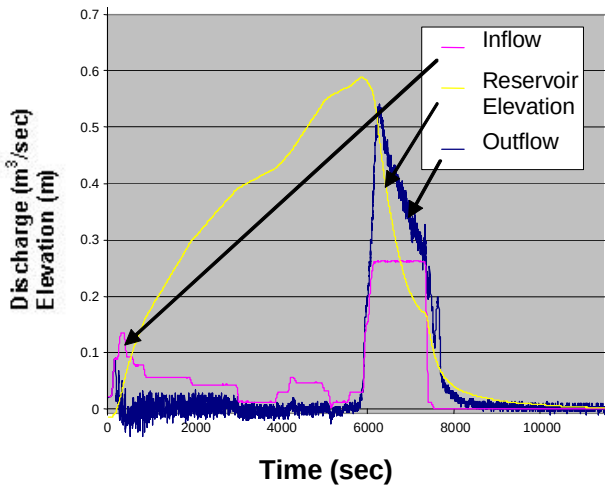

Figure 2. Example embankment overtopping and breach hydrograph.

2.2.2 Large-scale field tests of breach formation – Norway

Seven large-scale embankment tests have been conducted in Norway (Vaskinn et al., 2004). The Research Council of Norway provided funding to establish a research program in combination with contributions from Norwegian dam owners, the European Commission IMPACT project, and several other foreign sponsors. The total budget for the 2001-2004 program has been around 3 million US dollars.

The large-scale embankment test site is located in central Norway in Nordland County and the Hemnes Municipality near the town of Mo I Rana. Statkraft SF, Norway's biggest dam owner, allowed the use of the Rossvatn Dam spillway gates and reservoir to supply water to the test site located 600 m downstream (Figure 3). The reservoir volume created at this location for a 6-m high embankment is about 56,000 m^3 and the maximum inflow into the reservoir from the gates of the Rossvatn Dam is 450 m^3/s. The test site and test dams were instrumented and monitored to collect data on inflow and outflow, pore water pressures in the dam body, and detailed information on breach initiation, formation, and progression. Seven large-scale embankments 36-m long ranging in height from 4.5-6.0 m with upstream and downstream side slopes varying from 1.4 to 2.0 horizontal to 1 vertical, have been constructed and tested at this site. The materials tested included rockfill, glacial moraine, and cohesive marine clay.

Five of the tested embankments were failed by overtopping and two by piping failure. Only one of the embankments failed by overtopping was a cohesive embankment (Figure 4). The embankment had an initial central notch constructed to control the location of overtopping during testing. The grid painted on the downstream slope was for defining the scales on the photographs. The material used in the cohesive embankment was a marine clay with 28% clay content. During construction the soil was initially placed in 0.15 m layers and mechanically compacted with dozer tracks. Due to high water content in the borrow material (28 – 33%) and extremely wet weather conditions, construction of the test dam was difficult and construction procedures were

altered. The placement layer thickness was increased to 0.4 m, and the compaction pressure was reduced at a construction height of approximately 3 m. The average resulting compaction density was 1.47 g/cm^3. The test inflow, reservoir level, and breach outflow are shown in Figure 5.

2.2.3 Embankment overtopping research – US

The Agricultural Research Service (ARS) Hydraulic Engineering Research Unit at Stillwater, Oklahoma has historically conducted studies of the erosional failure processes of grass-lined earth emergency spillways. This research led to a 3-phase earth spillway erosion model that has been incorporated into the USDA Natural Resources Conservation Service (NRCS) SITES computer software. These research results have led to a natural progression of research in the area of embankment overtopping erosion and breach. The following four projects have been undertaken to extend the spillway erosion research into embankment overtopping erosion.

Figure 9. Test site location in Norway downstream of Rosvatn Dam.

Figure 10. Embankment overtopping setup.

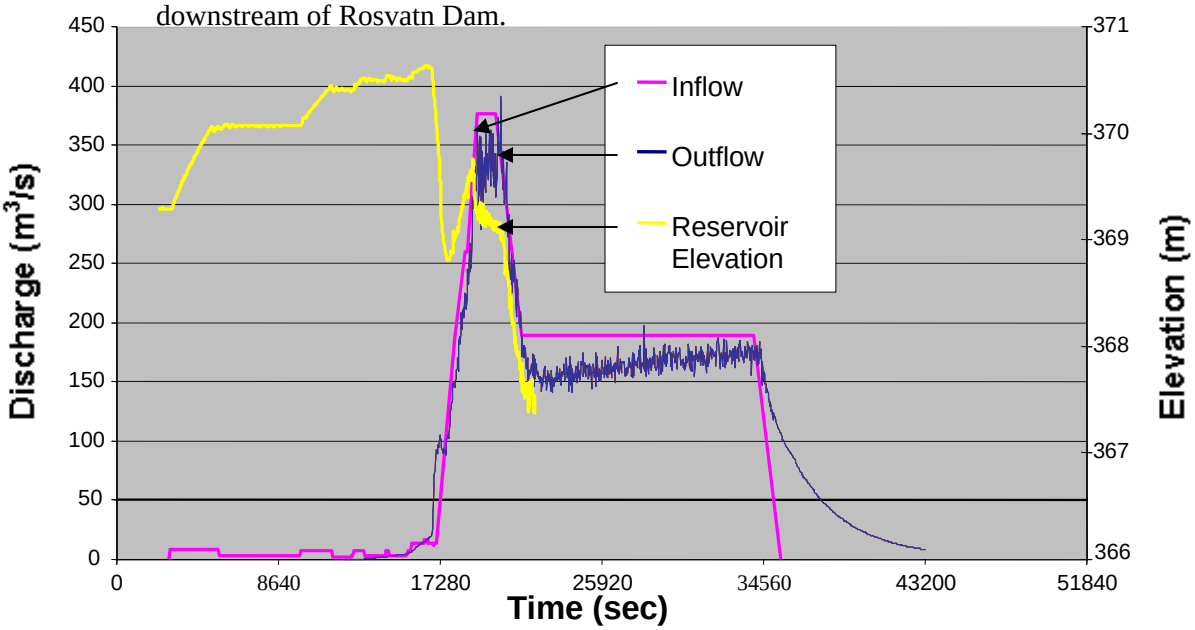

Figure 11. Embankment overtopping and breach hydrograph.

2.2.3.1 Steep grass and bare earth channel tests

An allowable stress design procedure (Temple et al., 1987) for grass-lined channels was developed from large-scale laboratory test data accumulated over the past 60 years. The procedure uses effective stress on the soil for the purpose of predicting incipient failure of the vegetated lining due to movement of the erodible boundary supporting vegetation.

Physical model tests to extend the research on vegetation in waterways and spillways to steep embankments were carried out on a 3-m high embankment constructed in the outdoor laboratory (Figure 6) (Hanson and Temple, 2002). After construction of the embankment, six 0.9-m wide channels were cut into the embankment to allow tests to be conducted on individual sections. The slope of the channels was 33% and the soil classified as ML to CL-ML in the Universal Soil Classification System. The embankment was compacted in 0.15 m lifts at and average compaction water content of 12% and specific weight of 1.8 g/cm^3. Tests were conducted on green bermudagrass, dormant bermudagrass, green fescue, and bare conditions. Effective overtopping depths for the tests ranged from 0.27 to 0.67 m. Duration of testing was up to 75 hr with mean velocities up to 5 m/s. Additional studies were conducted to evaluate the effect of surface discontinuities on the effectiveness of vegetal protection.

Figure 6. Example of steep channel tests.

2.2.3.2 Large-scale flume studies of headcut migration

Observations of spillway and embankment erosion confirm that the typical failure mode resulting in breach includes movement of a headcut through the hydraulic control section. Headcut advance tests were performed in a 1.8-m wide and 29-m long flume with 2.4-m high sidewalls (Figure 7) (Hanson et al. 2001). The test flume was filled by placing soil in horizontal loose layers 0.15 to 0.20 m thick. A 0.86-m wide vibratory padfoot roller was used to compact each layer, and a hand-held pneumatic compactor was used to compact the soil against the flume walls. Compactive effort and water content were varied from test to test. Prior to testing, a near vertical overfall was preformed at the downstream end of the test section. Overfall heights varied from 0.9 m

to 1.5 m. The dry unit weight and moisture content were determined as an average of the values determined from the density and strength samples for each test.

Headcut migration was monitored during each test (Figure 8). Even though headcut migration was observed to often be in discrete steps due to mass failures of the soil material at the headcut face, the global rate of movement for a set of flow conditions and soil material properties appeared to be uniform. Therefore, migration rates for each test were determined based on linear regression of the observed headcut position versus time. Headcut migration rates of two soils were examined in these flume experiments. These two soils were a red sandy clay soil (CL) and a silty sand soil (SM). A total of 46 tests were conducted using these two soils in various configurations and conditions. Six test cases of the CL material and one test case of SM material utilized compaction effort similar to that used on the same materials in the embankment overtopping tests conducted by the ARS as described later.

Figure 7. Headcut migration test in large outdoor flume.

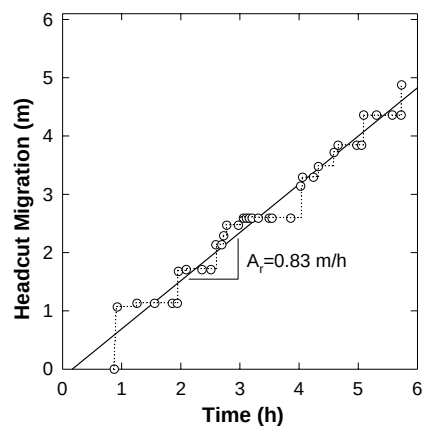

Figure 8. Typical observed headcut migration during a flume test.

2.2.3.3 *Large-scale tests of breach initiation and formation.*

Seven large-scale overtopping tests were conducted (Figure 9) to provide information relevant to the erosion processes of cohesive embankment breach failures. Hanson et al. (2003) provide a detailed description of these overtopping failure tests on 2.3-m and 1.5-m high cohesive embankments with 3 horizontal to 1 vertical upstream and downstream side-slope. Homogeneous embankments were constructed of three different soil materials, ranging from a silty-sand to a lean clay. The embankments were constructed in lifts, with a compaction lift thickness of 0.09 m. The soils were compacted using a self-propelled vibratory pad-foot roller. The compaction water content ranged from 9 to 18% for the seven tests. The resulting compaction densities ranged from 1.65 to 1.77 g/cm^3.

The inflow discharge stabilized quickly during each test, and was maintained at a relatively constant rate. The reservoir water level, embankment erosion, and discharge were measured throughout the duration of the tests, 4 to 72 hours. Inflow, outflow and reservoir elevation for one of the tests are shown in Figure 10 as an example.

2.2.3.4 Large-scale tests of breach widening.

Laboratory experiments are being conducted on homogeneous embankments to evaluate the widening of a breach over time following breach formation (Figure 6). The constructed embankments are 1.3 m in height with a 0.30-m wide notch down the center of the entire height of the embankment. The embankments have 3(H): 1(V) slopes on the upstream and downstream face. The embankments were constructed in lifts, with a compaction lift thickness of 0.09 m. The soils used in the tests were compacted using a self-propelled vibratory pad-foot roller. The inflow discharge stabilized quickly during each test, and the reservoir was maintained at a relatively constant level for a major portion of the test duration. The width of the breach opening was monitored over time to a maximum width of 5.5-m.

Figure 9. Embankment overtopping setup at ARS Hydraulic Laboratory

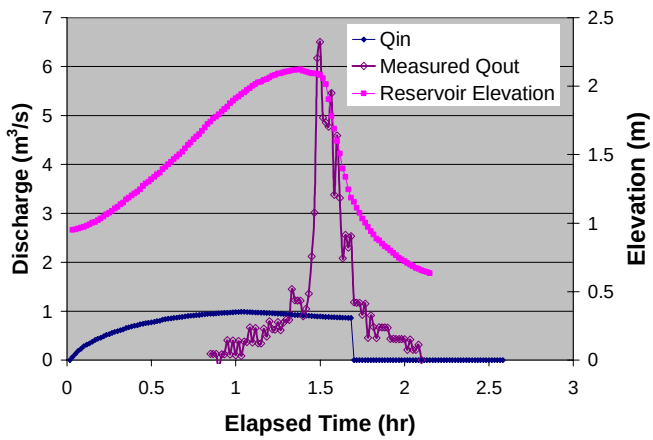

Figure 10. Example embankment overtopping and breach hydrograph.

Figure 11. Breach widening experiments.

2.3 Summary of Results Related to Cohesive Embankment Tests

A significant amount of information from these tests has been collected. Tables 2, 3, and 4 provide a summary of data for the tests conducted in the US, UK, and Norway including, embankment geometry, soil properties, and breach parameters.

Table 2. Summary of Cohesive Embankment Overtopping Tests**.**

Test Series	Embankment Dimensions					Notch Dimensions			Reservoir	
	Height (m)	Section Length (m)	Crest Width (m)	D.S. Slope	U.S. Slope	Bottom Width (m)	Depth (m)	Side Slopes	Storage Volume (m^3)	Inflow (m^3/s)
US-1	2.3	7.3	3	3:1	3:1	1.83	0.46	3:1	3787	1.0
-2	2.3	7.3	3	3:1	3:1	1.83	0.46	3:1	3975	1.0
- 3	2.3	7.3	3	3:1	3:1	1.83	0.46	3:1	3942	1.0
- 4	1.5	4.9	2	3:1	3:1	1.22	0.30	3:1	4404	1.0
- 5	1.5	4.9	2	3:1	3:1	1.22	0.30	3:1	4552	1.0
- 6	1.5	4.9	2	3:1	3:1	1.22	0.30	3:1	4368	0.33
- 7	2.1	12.2	3	3:1	3:1	8.23	0.30	3:1	4094	1.93
UK-1	0.6	4.0	0.2	2:1	2:1	0.54	0.05	2:1	244	0.02-0.26
-2	0.6	4.0	0.2	2:1	2:1	0.54	0.05	2:1	244	0.02-0.26
-3	0.6	4.0	0.2	2:1	2:1	0.54	0.05	2:1	244	0.03-0.27
-4	0.6	4.0	0.2	2:1	2:1	0.54	0.05	2:1	244	0.02-0.09
-5	0.6	4.0	0.2	2:1	2:1	0.54	0.05	2:1	244	0.10-0.27
-6	0.6	4.0	0.2	1:1	2:1	0.54	0.05	2:1	244	0.03-0.26
-7	0.6	4.0	0.2	3:1	2:1	0.54	0.05	2:1	244	0.02-0.26
N –2	6.0	36	2.0	2.3:1	2.4:1	6.65	0.45	1:1	56000	1-350

Table 3. Summary of Material Properties for Cohesive Embankment Tests.

Test Series	Classification Parameters[1]				Compaction	
	Sand % >0.105 mm	Clay % <0.002 mm	PI[2]	USCS[3]	WC[4] %	γ_d[5] (g/cm^2)
US -1	70	5	NP	SM	8.7	1.72
- 2	25	26	17	CL	16.4	1.65
- 3	63	6	NP	SM	12.1	1.73
-4	67	3	NP	SM	11.5	1.73
-5	27	26	16	CL	17.8	1.67
-6	65	6	NP	SM	14.5	1.74
-7	64	6	NP	SM	11.5	1.77
UK -1	0	43	35	CH	24.6	1.20
-2	0	43	35	CH	23.7	1.20
-3	0	43	35	CH	21.5	1.10
-4	0	43	35	CH	27.9	1.23
-5	0	43	35	CH	27.9	1.23
-6	0	43	35	CH	19.6	1.16
-7	0	43	35	CH	19.2	1.13
N – 2	5	30	13	CL	30.0	1.47

[1]Tests by USDA-NRCS Soil Mechanics Center. [2]PI – Plasticity Index, [3]USCS – Universal Soil Classification System, [4]WC – water content, [5]γ_d – dry unit weight.

Table 4. Embankment overtopping breach results.

Test Series	Breach Values (Following Overtopping)				Headcut Migration Rate, dX/dt		Downcutting Rate, dZ/dt
	Breach[1] Initiation Time (sec)	Breach[1] Formation Time (sec)	Final Breach Width (m)	Peak Discharge (m^3/s)	Stage II[1] (m/hr)	Stage III[1] (m/hr)	Stage III[1] (m/hr)
US -1	1860	1200	6.9	6.5	7.4	15.7	5.5
-2	>72000	-	-	-	0.14	-	-
-3	19200	5990	6.2	1.8	0.68	2.3	1.1
-4	2400	4000	3.3	2.3	7.6	2.4	1.1
-5	>260000	-	-	-	0.04	-	-
-6	70320	21960	3.3	1.3	0.23	0.28	0.2
-7	18420	3140	4.5	4.2	1.3	3.1	2.1
UK -1	840	4400	1.83	0.31	0.86	0.90	0.45
-2	840	3670	1.69	0.34	0.86	1.08	0.54
-3	513	1477	2.60	0.53	1.4	2.68	1.34
-4	-	-	-	-	0.26	-	-
-5	-	11194	1.33	0.28	-	0.36	0.18
-6	212	2829	1.73	0.35	3.40	1.40	0.70
-7	248	1740	2.34	0.43	2.90	2.28	1.14
N –2	6540	566	22.7	390	1.10	49	35

[1] Terms for breach initiation, formation, and stages defined in section, "LESSONS LEARNED."

2.4 Lessons Learned from Cohesive Embankment Breach Tests

2.4.1 Observed erosion processes of cohesive embankments

Observations and data recorded during overtopping of the seven ARS embankments testsd, led to a four-stage description of the embankment breach processes (Hanson et al., 2003):

I. Flow over the embankment initiates at $t = t_0$. Initial overtopping flow results in sheet and rill erosion with one or more master rills developing into a series of cascading overfalls (Figure 12a). Cascading overfalls develop into a large headcut (Figure 12b and 12c). This stage ends with the formation of a large headcut at the downstream crest and the width of erosion approximately equal to the width of flow at the downstream crest at $t = t_1$,
II. The headcut migrates from the downstream to the upstream edge of the embankmet crest. The erosion widening occurs due to mass wasting of material from the banks of the gully. This stage ends when the headcut reaches the upstream crest at $t = t_2$ (Figure 12d),
III. The headcut migrates into the reservoir lowering of the crest occurs during this stage and ends when downward erosion has virtually stopped at $t = t_3$ (Figure 12e). Because of the small reservoir size, the peak discharge and primary water surface lowering occurred during this stage, and

IV. During this stage breach widening occurs and the reservoir drains through the breach area (Figure 12f). In larger reservoirs, the peak discharge and primary water surface lowering would occur during this stage ($t_3 < t \leq t_4$) rather than during stage III. This stage may be broken into two stages for larger reservoirs depending on the upstream head through the breach.

Figure 12. Generalized description of observed erosion processes during ARS overtopping tests: a) rills and cascade of small overfalls during Stage I, b) consolidation of small overfalls during Stage I, c) headcut at downstream crest, transition from Stage I to Stage II, d) headcut at upstream crest, transition from Stage II to Stage III at breach initiation $t = t_i$, e) flow through breach during Stage III, and f) transition from Stage III to Stage IV at breach formation $t = t_f$.

Figure 13. Observed headcut erosion during cohesive embankment overtopping test in Norway

Figure 14. Curved weir control section during breach formation during Norway test.

Stages I and II encompass the time period of breach initiation up to $t = t_i$, and Stage III encompasses the time period referred to as breach formation $t = t_f$. These stages as described are a generalization of the processes that were observed. These same general processes were observed in the tests conducted in Norway (Figure 13) and the UK. In addition to the observed stages of erosion and headcut formation and migration as one of the dominant erosion processes, other observations included: 1) Vertical or nearly vertical sidewalls during erosion and breach widening in all test cases (Figures 12-14); and 2) Formation of an arch-type weir during breach formation (Figure 14).

2.4.2 Initiation and formation time

Wahl (1998) defined breach initiation time as the time that spans from the first flow over the dam to the point of lowering of the upstream embankment crest of the dam and breach formation times as the time that spans from the point of lowering of the upstream embankment crest of the dam to the point at which the upstream face is eroded to full depth of the dam. The breach initiation time can be important in determining hazard downstream, warning time, and evacuation planning. Breach initiation involves stages I and II as described previously. The steep channel vegetation tests indicate that vegetation can increase the length of time for breach initiation and within certain flow durations and stresses the vegetation may prevent breach initiation altogether. Results from embankment overtopping tests at the ARS, HR Wallingford, and Norway also indicate that breach initiation time can be quite lengthy and often greater than breach formation time. Breach initiation times were observed to range from a low of 0.07 to 11.6 times the breach formation time (Table 4). Two of the ARS tests were observed to still be in breach initiation at the end of the tests after overtopping durations of 20 and

72 hours (Table 4). The breach initiation time is dependent on embankment vegetation, material type and placement, embankment geometry, reservoir storage, and discharge.

2.4.3 Rate of erosion and compaction effects

Walder and O'Connor (1997) point out the importance of breach erosion rate, in addition to reservoir volume and dam embankment height, for determining peak discharge. Hassan et al. 2004 observed that a decrease in compaction energy and water content of the embankment accelerated the erosion process, which led to higher peak outflow and large final breach width. Erosion rate not only impacts peak discharge and final breach width but also affects the amount of erosion damage, breach initiation time, breach formation time, and rate of breach widening. As an example, headcut erosion is one of the key erosion processes observed during cohesive embankment overtopping (Figure 12). The flume headcut migration tests conducted by the ARS indicate that the rate of headcut migration and breach erosion is impacted by placement compaction energy and water content (Hanson and Cook, 2004). Inspection of a simple headcut migration equation developed by Temple (1992) indicates that the rate of headcut migration dX/dt is a function of the unit discharge q, headcut height H, and C a headcut migration coefficient:

$$dX/dt = C(qH)^{1/3} \qquad [1]$$

The headcut migration coefficient C is a function of the material properties. A preliminary comparison of calculated C values for the ARS flume and the ARS, HR Wallingford, and Norway embankment test results for Stages I and II is shown in Figure 15. These results indicate: 1) the compaction energy for the ARS flume and ARS embankment tests were equivalent indicating a consistency in C values for these two different test environments; 2) for the six different cohesive soils used in the ARS flume and embankment tests, the C value is dependent on the compaction energy and water content; 3) the compaction water content has a significant effect on the headcut migration coefficient; and 4) the compaction energy used in the construction of HR Wallingford and Norway embankments was significantly less than the compaction energy used in the ARS flume and embankment tests. This difference in compaction energy resulted in a significant shift upward for the results of C, but a similar slope for C versus compaction water content was retained.

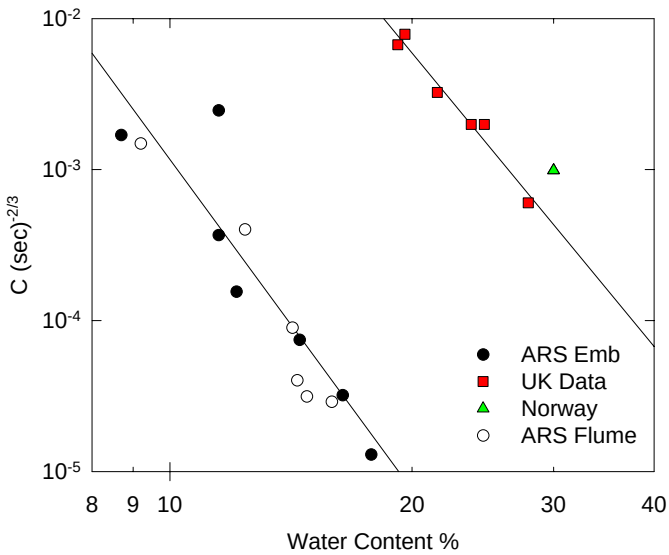

Figure 15. Headcut migration coefficient for flume and embankment test results.

Integrating the results from the different tests that have been conducted will be important in developing numerical models to predict breaching. One of the key

requirements in modeling will be the development of approaches to determine appropriate input parameters for identifying processes and predicting erosion rates.

3.0 WORKSHOP

The one day workshop was held at the Annual Conference of the Association of State Dam Safety Officials 2004 Dam Safety. The title of the day long workshop was; "Workshop on International Progress in Dam Breach Evaluation." Ten presentations were included in the workshop. Even though the primary focus of the research interaction described in section 2.0 was on cohesive embankment overtopping and failure testing, data collection, and integration; the workshop included a broader scope of papers. The workshop covered subject matters related to embankment failure and flooding such as: embankment overtopping and failure testing of cohesive, non-ochesive, and rockfill embankments; geophysical measurements of embankments and material property implications related to embankment breach; flood propogation, sediment movement, and embankment dam breach modeling; and risk and uncertainty related to flooding. The broad scope of the workshop reflects not only the concerns in Europe related to dam failures and flooding but also the concerns in the USA.

Note: The papers in the workshop do not describe all of the research being conducted in Europe or the US but provide an overview of the effort and insight into the current state of the science. In order to understand in fuller detail the research being conducted in Europe related to flooding, a network described at the following link http://www.crue-eranet.net/ , has been established. The purpose of the CRUE network is to 1) consolidated European flood research programs, promote best practice and identify gaps and opportunities for collaboration on future research program content. At present it consists of 13 European countries that have been particularly affected by flooding.

3.1 Summary of Workshop Papers (see appendix for actual manuscripts)

3.1.1 Paper 1 –
CADAM / IMPACT / FLOODSITE: A concerted, long-term research effort on dam safety, risk, dam failure prediction, sediment transport, and flooding –
Authors: Mark Morris, UK; Yves Zech and Sandra Soares Frazao, Belgium; Francisco Alcrudo, Spain; and Zuzanna Boulalova, Czech Republic.

This paper reviews the research covered in the three European Commission Projects (CADAM, IMPACT, and FLOODSITE). These three projects have resulted in concerted long term research in Europe to investigate 1) breaching of embankments, 2) flood inundation and routing, 3) mechanisms of sediment movement, 4) geophysical methods to assess embankment integrity and 5) uncertainty and risk related to flood defenses and prediction.

3.1.2 Paper 2 –

Physical Modeling of Breach Formation; Large Scale Field Tests – *Authors:* Kjetil Arne Vaskinn, Aslak Lovoll, and Kaare Hoeg, Norway; Mark Morris and Mohamed Hassan, UK; and Greg Hanson, USA

This paper describes the large scale physical modeling of embankment erosion and failure due to overtopping and internal erosion. The tests have been conducted on 5 to 6m embankments constructed in the middle of Norway near the town of Mo I Rana. The test site was located about 600 m downstream of the Rossvassdammen Dam which made it possible to control inflow to the test site. A total of 7 field tests were performed on cohesive, and non-cohesive materials (i.e. moraine and rockfill). The structures were failed by overtopping and internal erosion with the purpose of observing erosion processes, rates of erosion, and rates of resulting discharge. One of the key erosion processe observed was headcut development and migration. It was interesting to note that headcutting was even observed in the non-cohesive rockfill structures.

3.1.3 Paper 3 –

Breach Formation: Laboratory and Numerical Modeling of Breach Formation – *Authors:* Mohamed Hassan, and Mark Morris, UK; Greg Hanson, USA; and Karim Lakhal, France

This paper describes the small scale testing that was conducted on 0.5 to 0.6 m height non-cohesive and cohesive embankments as well as numerical model development and comparisons using the physical model results. A total of 22 laboratory embankment failures tests were conducted. The physical model results indicated the importance of embankment geometry, breach location, erosion processes, erosion rate, and material type and placement on embankment breach. Numerical model results and performance were also compared in this paper. Not all numerical models were compared against all physical model results.

3.1.4 Paper 4 –

Case Studies and Geophysical Methods – *Authors:* Vojt ch Bene, Zuzana Boukalova, Michal Tesal, and Vojt ch Zikmund, Czech Republic

Results from geophysical measurements at selected locations in the Czech republic are present in this paper. A framework design for a dike breach parameters database is also presented. It is concluded in this paper that a combination of geophysical methods is appropriate for determining preventive repair and maintenance needs of embankments. The suggested combination of geophysical methods fall into three basic categories: 1) rapid testing methods, 2) diagnostic methods, and 3) monitoring methods.

3.1.5 Paper 5 –

Flood Propagation Model Development – *Authors:* Francisco Alcrudo, Spain; Sandra Soares-Frazao, Yves Zech, Guido Testa, Andre Paquier, Jonatan Mulet, David Zuccala, and Karl Broich

This paper provides a review of the main issues and research being conducted concerning flood propagation, model development, and validation. Experimental set-up and data collection for validating the Shallow Water Equations flood routing models described in this paper fall into two types; 1) very simple geometric configurations in which the flooding is idealized and 2) scale physical models of actual topographies. Two of the idealized configurations include a dam break flow in a flume with an isolated building and another with an idealized hillside. One of the scale physical models is a 1:100 scale of a reach of the Alpine River Toce and another physical model described in this paper is of a model city flooding experiment.

3.1.6 Paper 6 –

Sediment Movement Model Development – *Authors:* Yvez Zech, and Sandra Soares-Frazao, Belgium; Benoit Spinewine and Nicolas Ie Grelle, Belgium; Aronne Armanini, Luigi Fraccarrollo, Michele Larcher, Rocco Fabrizi, and Matteo Giuliani, Italy; Andre Paquier and Kamal El Kadi, France; Fui M. Ferreira, Joao G.A.B. Leal, Antonio H. Cardoso, and Antonio B. Almeida, Portugal

This paper presents aspects of sediment movement modeling related to a flood wave following a dam-break. The difficulty in modeling dam-break flows is that they involve rapid changes and intense rates of transport. This paper reviews physical and numerical modeling of the near-field behavior and far field behavior related to sediment movement following a dam break.

3.1.7 Paper 7 –

Process Uncertainty: Assessing and Combining Uncertainty Between Models – *Authors:* Mark Morris, UK; Francisco Alcrudo, Spain; Yves Zech, Belgium; and Karim Lakhal, France

This paper identifies the advances that have been made relative to uncertainty associated with breach formation, flood propogation, and sediment movement and the importance to risk management of flood defenses. A methodology is described for combining sensitivity analysis, Monte Carlo analysis and expert judgement to allow assessment of modeling uncertainty and integration of uncertainty between models.

3.1.8 Paper 8 –

Determination of Material Rate Parameters for Headcut Migration of Compacted Earthen Materials – *Authors:* Gregory J. Hanson, and Kevin R. Cook, USA

This paper recognizes the importance of embankment material properties on embankment erosion and failure. The rate of embankment failure can dramatically impact the rate of water released from a reservoir and the resulting downstream peak flooding and duration of flooding. Headcut development and migration is recognized as one of the key erosion processes related to overtopping of cohesive embankments. Flume test results and observerd impact of material types and placement of the soil materials on rate of headcut migration are discussed in this paper.

3.1.9 Paper 9 –

Simulation of Cascading Dam Breaks and GIS-based Consequence Assessment: A Swedish Case Study – *Authors:* Romanas Ascila, and Claes-Olof Brandesten, Sweden

This paper describes the use and development of an integrated approach in Sweden that looks at dam-break modeling over an entire system including potentially a cascade of dams. A specific study area presented in the paper is a dam cascade situated on the river Lilla Lule Alv in the northern part of Sweden. This study covers eight dams. The methodology covers procedures for data collection and processing, hydraulic modeling, GIS integration and modeling, and consequence analysis and dissemination of the results. This approach enables the simulation of the whole system and provides a better understanding of possible consequences and identified system needs.

3.1.10 Paper 10 - Two Dimensional Model for Embankment Dam Breach Formation and Flood Wave Generation – *Authors:* David C. Froehlich, USA

This paper describes a two-dimensional depth-averaged breach model including assumptions, inputs, governing equations, formulations, and computation simulation results. The simulations results described in this paper are based on data from the large-scale earthen embankment experimental erosion tests conducted in Norway described in paper 2 of this workshop.

4.0 CONCLUSION

Study of the erosion mechanics of overtopping flow of cohesive embankments in Europe and the US has advanced the science in a number of areas including: vegetation effects, erosion processes, erosion rates, failure timing, breach hydrograph, material type and placement effects, and scaling. There is still much work to be conducted to integrate the work described in this report to continue the formulation of a cohesive embankment breach model. Work, as described in the papers presented in the workshop (Appendix), has begun the development of computational models, and risk analysis based on the physical modeling results. The value of integrating research programs nationally and internationally has been recognized and cooperation is ongoing. Effective integration of this work avoids duplication of research effort and allows ideas and concepts from a wider range of sources to be considered.

The Federal Emergency Management Agency through the National Dam Safety Program provided the resources to coordinate the ongoing efforts described in the report for the benefit of the dam safety community.

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