Hydraulic Design of Stepped Spillways

James Ruff
and
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Project Background

- Continuation of Dam Safety Research
  - Cooperative agreement between CSU & USBR
  - spillway overtopping flows
  - near prototype scale test facility
- Stepped Spillway Phase
  - Start of construction July 1999
  - Two summers of testing
  - Data analysis and report 2000-2001

Overtopping Facility

- Near-prototype scale
- 2H:1V Slope
- 100 ft concrete chute
- 50ft height
- 10ft wide
  - reduced to 4 ft
- 5 ft deep
  - 7 ft extended height
- Horsetooth water supply
  - approx. 120 cfs max

Objective

Collect data on the characteristics of stepped spillway flow and develop a hydraulic design procedure.

Experimental Program

- Air concentration data
- Velocity data
- Visual Observations
  - Range of discharges & locations
  - Two step heights

Test Series

Stepped Spillway Tests

- Horizontal Steps
- Constructed of lumber and plywood

Smooth Spillway Tests

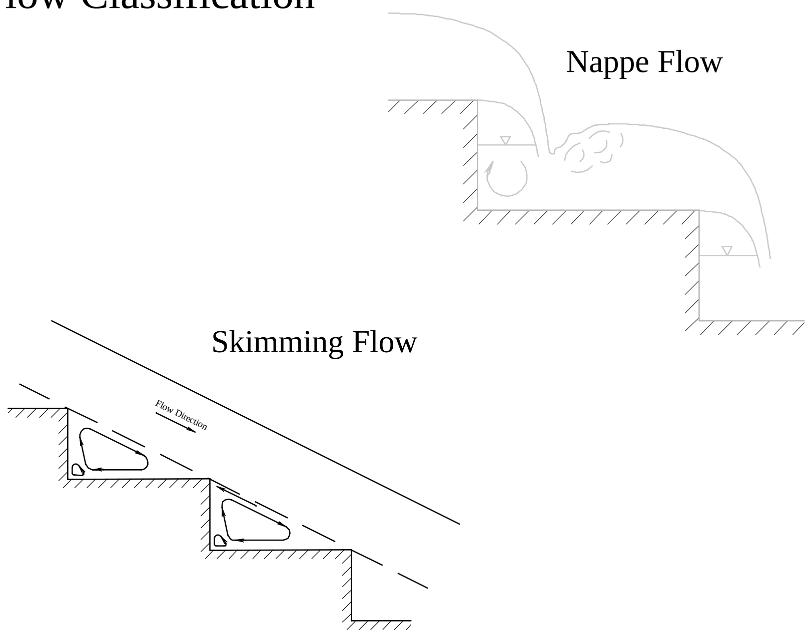
- Steps removed
- Comparison data

- First Series
  - 25 two-foot steps
  - 4 ft tread length
  - 2 ft riser height

- Second Series
  - 50 two-foot steps
  - 2 ft tread length
  - 1 ft riser height

- Third Series
  - Steps removed
  - Comparison data

Flow Classification



Observations

h = 2.0 ft

Transition
Q = 40 cfs
Window # 4

Nappe
Q = 20 cfs
Window # 4

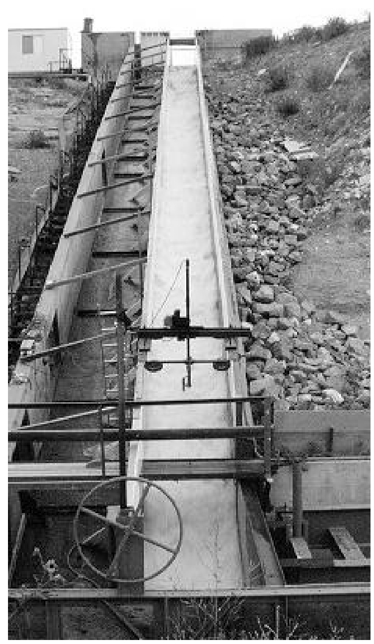
Skimming
Q = 60 cfs
Window # 3

Observations, cont'd

h = 1.0 ft

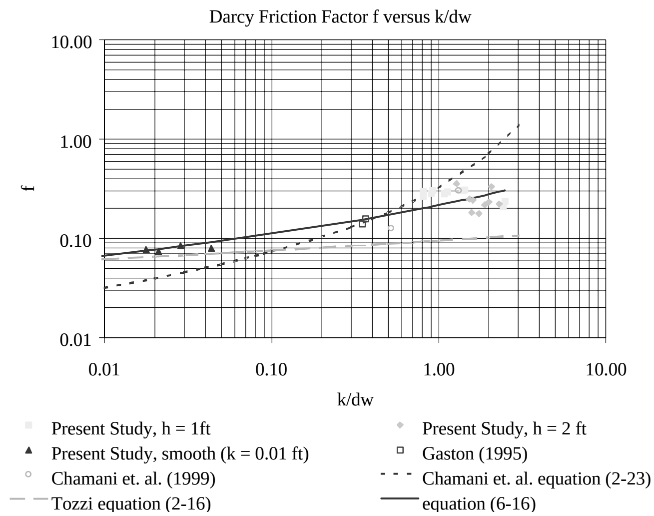
Nappe
Q = 7.1 cfs
Window # 2

Skimming
Q = 21 cfs
Window # 4



h = 1.0 ft
Q = 60 cfs

Friction Factor

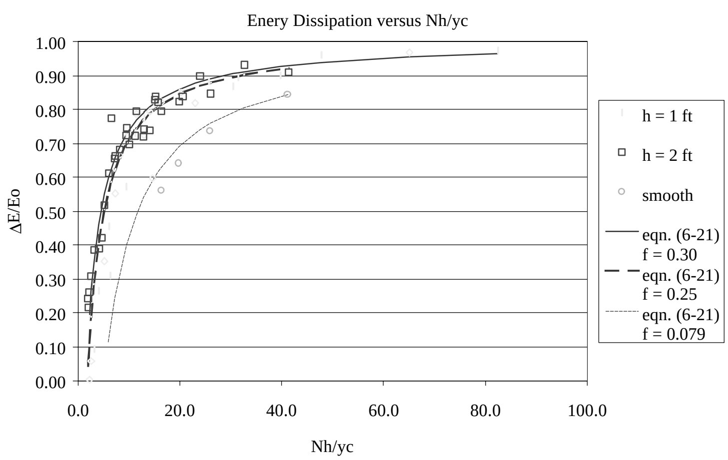


$$f = \frac{8 g d_w S_f}{U_{avg}^2}$$

$$\frac{1}{\sqrt{f}} = 2.15 + 0.85 \log\left(\frac{d_w}{k}\right)$$

k = roughness height
dw = clear water depth

Energy Dissipation, cont'd



Energy Dissipation

$$\frac{\Delta E}{E_o} = \frac{E_o - E_1}{E_o}$$

$$\frac{\Delta E}{E_o} = 1 - \frac{\left(\frac{f}{8\sin\theta}\right)^{\frac{1}{3}}\cos\theta + \frac{1}{2}\left(\frac{f}{8\sin\theta}\right)^{-\frac{2}{3}}}{\frac{Nh}{y_c} + \frac{3}{2}}$$

N = number of steps
h = step height
yc = critical depth

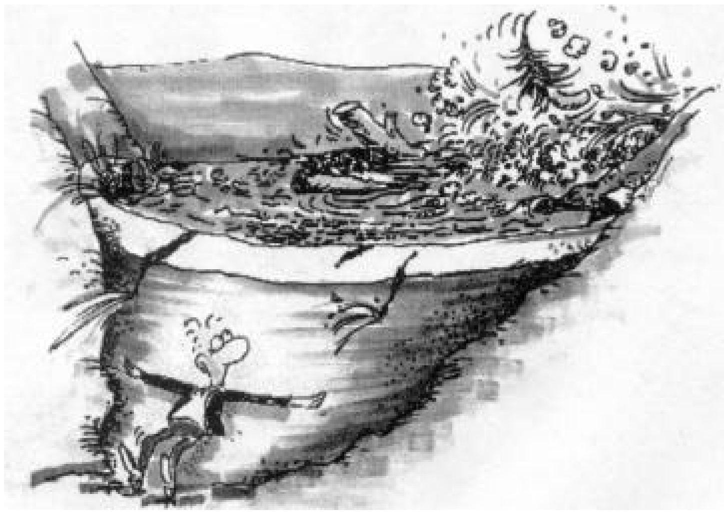
Hydraulic Design Procedure

- Assume given information
  - Total discharge, Q
  - spillway width, b
  - spillway height, H
  - spillway slope, $\theta = 26.6^{\circ}$
  - select step height, h (1.0 ft or 2.0 ft)
- Design Charts:
  - friction factor $f = \mathrm{f}(H, q)$ versus Nh/y_c
  - bulking coefficient $\varepsilon = \mathrm{f}(H,q)$ versus Nh/y_c
- Water surface profile computation with f
  - d_w, U_{avg}
- Compute energy dissipation

Hydraulic Analysis of Articulated Concrete Blocks

Christopher Thornton,Steven Abt,
Chad Lipscomb and Michael Robeson

Recent Developments in the Research and Development of Articulating Concrete Blocks for Embankment Overtopping Protection

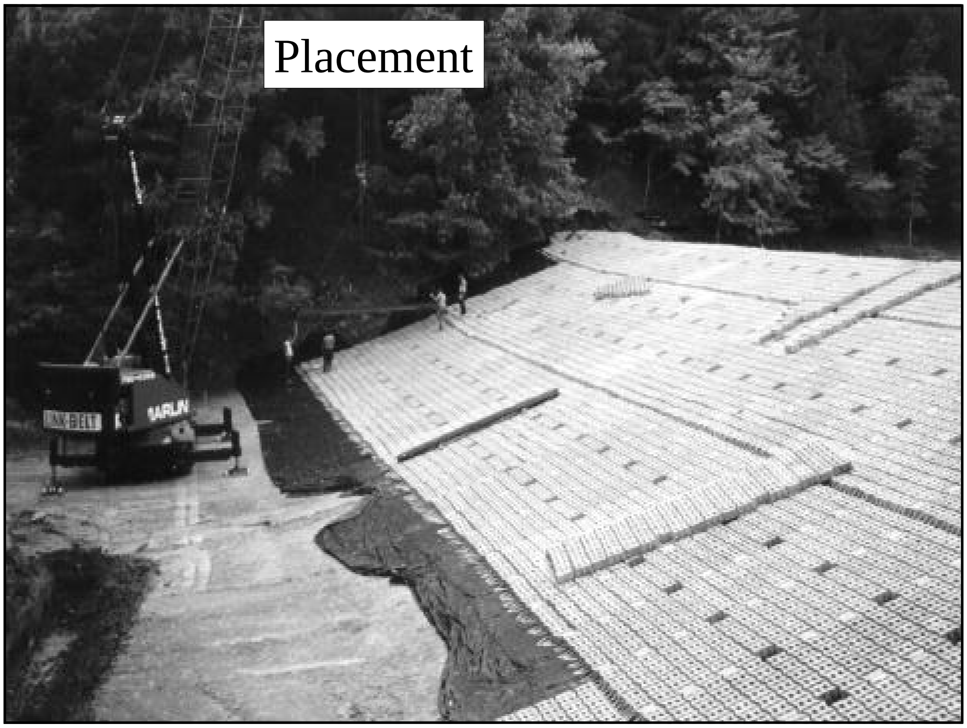


Purpose

- To evaluate the performance of commercially available embankment protection systems under various hydraulic conditions
- To develop design criteria for ACB systems
- To determine the effect of a drainage medium under ACB systems

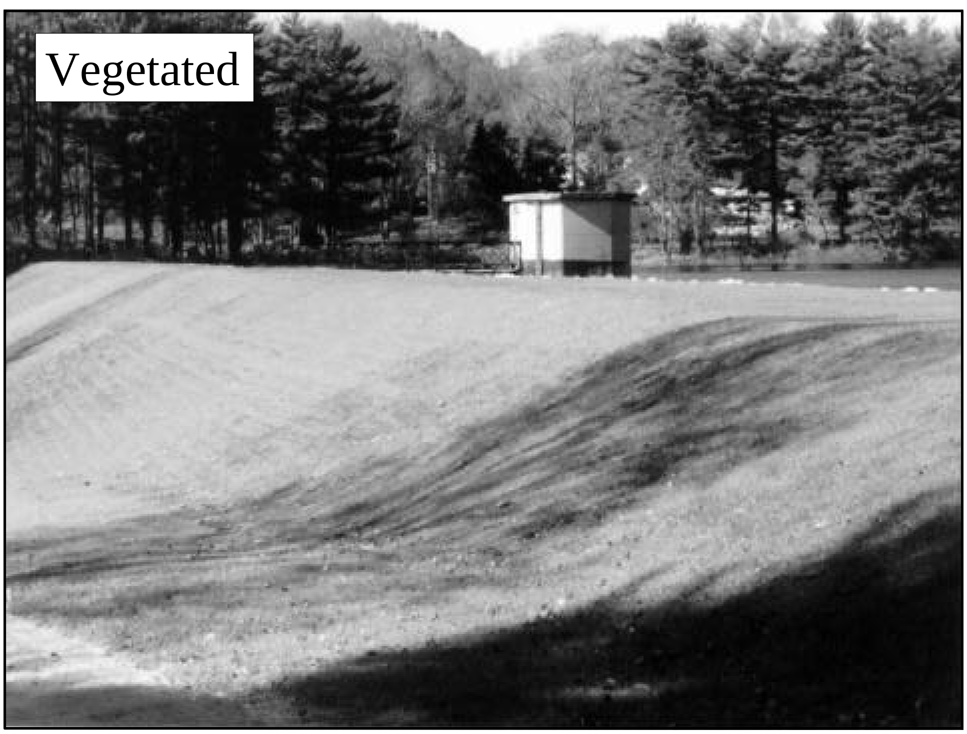
ACB Mats

Placement

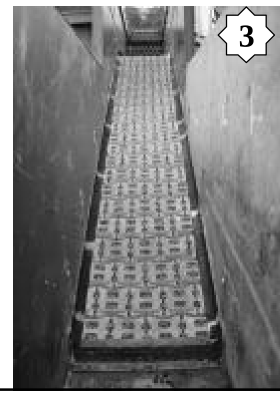

Placement


Un-Vegetated


Vegetated


Vegetated

Block Overtopping Tests
Flume Setup



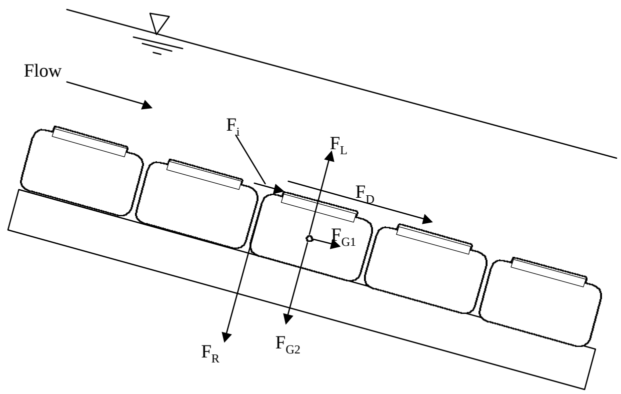
Overtopping Testing

Overtopping Testing

Threshold Levels

Threshold Levels

Force Balance



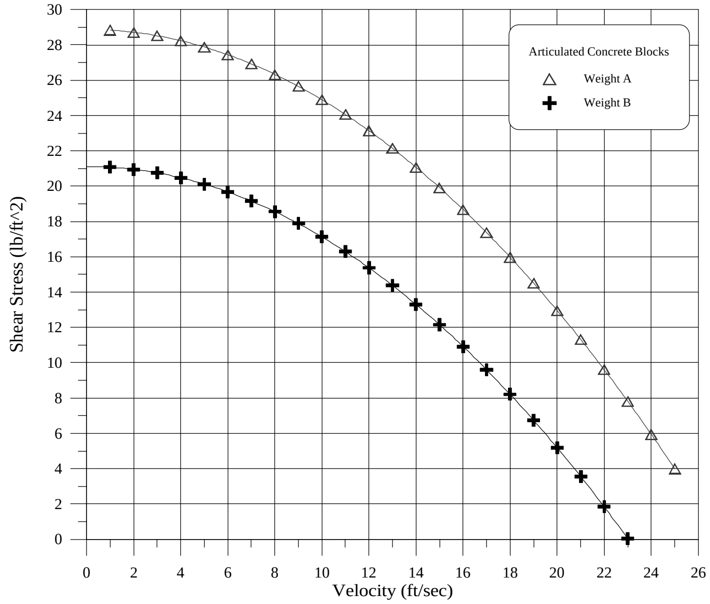
Destabilizing Forces

F_i = Impact force (projecting block)
F_L = Lift Force
F_D = Drag Force
F_{G1} = Gravity force parallel to slope

Stabilizing Forces

F_R = Interblock resistance
F_{G2} = Gravity force normal to slope

Design Curves



Results

- Drainage layer has pronounced effect on system performance
- At high flows, velocity appears to be dominant force
- Performance values consistent between overtopping and channelized test protocols

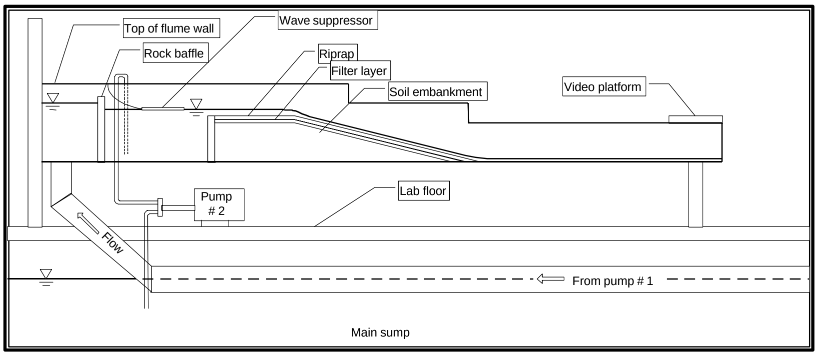
Design Criteria for Rounded Rock Riprap

Steven Abt
and
Humberto Gallegos

Purpose

- Develop design criteria for rounded/angular rock riprap in overtopping flow
- Expand the database of rounded rock riprap to include higher embankment slopes
- Increase the understanding of the behavior of rounded rock riprap in overtopping flow

Flume Setup



Flume Setup

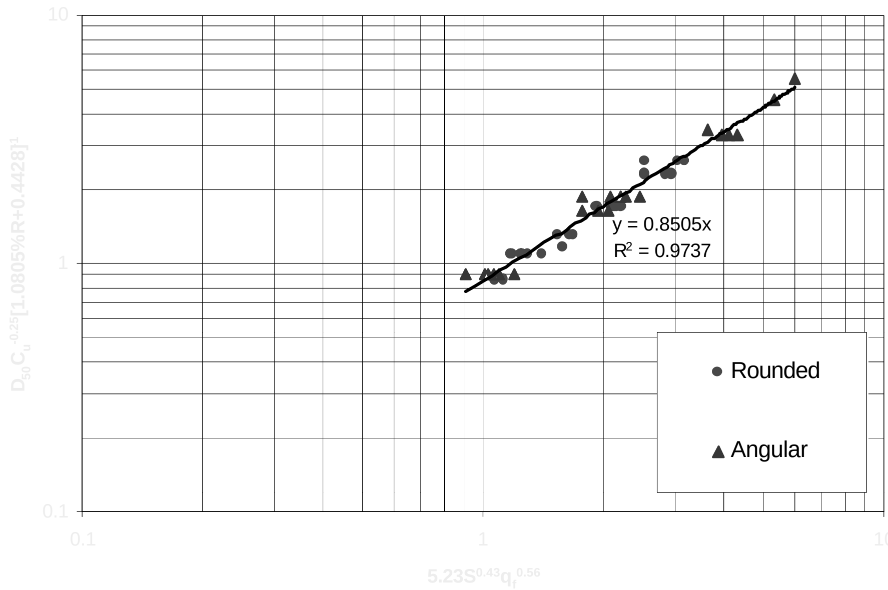
Testing Matrix

Test #	D_{50}	D_{50}	C_u	% Rounded	S
	(cm)	(in)			decimal
1	5.87	2.31	1.21	79	0.35
2	3.23	1.27	1.32	60	0.35
3	9.91	3.90	1.24	92	0.35
4	5.87	2.31	1.21	79	0.40
5	3.23	1.27	1.32	60	0.40
6	9.91	3.90	1.24	92	0.40
7	3.23	1.27	1.32	60	0.45
8	5.87	2.31	1.21	79	0.45
9	9.91	3.90	1.24	92	0.45

Cumulative Database

			D_{50}	D_{50}	C_u	Rounded	S	q_f	q_f	Mode Of
			(cm)	(in)		%	decimal	$m^3/s/m$	$ft^3/s/ft$	Failure
Current Study	1	Round	5.87	2.31	1.21	79	0.35	0.042	0.465	Exposure
	2	Round	3.23	1.27	1.32	60	0.35	0.014	0.164	Catastrophic
	3	Round	9.91	3.90	1.24	92	0.35	0.086	0.935	Exposure
	4	Round	5.87	2.31	1.21	79	0.40	0.021	0.235	Channel
	5	Round	3.23	1.27	1.32	60	0.40	0.014	0.157	Channel
	6	Round	9.91	3.90	1.24	92	0.40	0.051	0.552	Exposure
	7	Round	3.23	1.27	1.32	60	0.45	0.012	0.131	Exposure
	8	Round	5.87	2.31	1.21	79	0.45	0.036	0.394	Catastrophic
	9	Round	9.91	3.90	1.24	92	0.45	0.065	0.708	Exposure
Ullmann (2000)	10	Round	2.39	0.94	1.24	55	0.20	0.019	0.20	Channel
	11	Round	2.39	0.94	1.24	55	0.30	0.016	0.18	Channel
	12	Round	3.23	1.27	1.32	60	0.20	0.020	0.23	Channel
	13	Round	3.23	1.27	1.32	60	0.25	0.021	0.22	Channel
	14	Round	3.23	1.27	1.32	60	0.30	0.019	0.21	Channel
	15	Round	4.50	1.77	1.33	75	0.20	0.035	0.39	Channel
	16	Round	4.50	1.77	1.33	75	0.25	0.035	0.38	Channel
	17	Round	4.50	1.77	1.33	75	0.30	0.029	0.32	Channel
	18	Round	5.87	2.31	1.21	79	0.20	0.053	0.58	Catastrophic
	19	Round	5.87	2.31	1.21	79	0.30	0.049	0.53	Catastrophic
	20	Round	5.87	2.31	1.21	79	0.25	0.052	0.57	Catastrophic
	21	Round	9.91	3.90	1.24	92	0.30	0.096	1.04	Catastrophic
Abt et al. (1988 a)	22	Round	10.42	4.10	2.12	95	0.20	0.087	0.96	Unknown
	23	Round	10.42	4.10	2.12	95	0.20	0.087	0.96	Unknown
	24	Round	10.42	4.10	2.12	95	0.10	0.183	1.99	Unknown
	25	Round	10.42	4.10	2.12	95	0.10	0.192	2.09	Unknown
	26	Round	5.21	2.05	2.14	95	0.10	0.063	0.69	Unknown
Abt and Johnson (1991)	1	Angular	2.59	1.02	1.75	0	0.02	0.102	1.11	Unknown
	2	Angular	2.59	1.02	1.75	0	0.01	0.138	1.50	Unknown
	3	Angular	2.59	1.02	1.75	0	0.10	0.023	0.26	Unknown
	4	Angular	2.59	1.02	1.75	0	0.10	0.031	0.34	Unknown
	5	Angular	2.59	1.02	1.75	0	0.10	0.028	0.31	Unknown
	6	Angular	2.59	1.02	1.75	0	0.10	0.039	0.42	Unknown
	7	Angular	5.08	2.00	2.40	0	0.10	0.078	0.86	Unknown
	8	Angular	5.08	2.00	2.40	0	0.10	0.092	1.00	Unknown
	9	Angular	5.08	2.00	2.40	0	0.10	0.102	1.11	Unknown
	10	Angular	5.59	2.20	2.09	0	0.10	0.103	1.12	Unknown
	11	Angular	5.59	2.20	2.09	0	0.10	0.115	1.25	Unknown
	12	Angular	5.59	2.20	2.09	0	0.10	0.116	1.26	Unknown
	13	Angular	5.59	2.20	2.09	0	0.08	0.166	1.81	Unknown
	14	Angular	5.59	2.20	2.09	0	0.02	0.416	4.53	Unknown
	15	Angular	5.59	2.20	2.09	0	0.20	0.046	0.50	Unknown
	16	Angular	10.16	4.00	2.30	0	0.10	0.232	2.51	Unknown
	17	Angular	10.16	4.00	2.30	0	0.10	0.348	3.79	Unknown
	18	Angular	10.16	4.00	2.30	0	0.10	0.379	4.12	Unknown
	19	Angular	10.41	4.10	2.16	0	0.20	0.166	1.81	Unknown
	20	Angular	12.95	5.10	1.62	0	0.20	0.327	3.56	Unknown
	21	Angular	15.75	6.20	1.69	0	0.20	0.407	4.43	Unknown

Analysis



Results

$$D_{50} = 6.58S^{0.43}q_f^{0.56}C_u^{0.25}(1.0805\%R=0.4428)$$

•Embankment Slopes:	10 to 45 %
•Median Rock Sizes:	D_{50} = 2.4 to 15.3 cm
•Rounded Rock:	55 to 95 %
•Riprap Layer Thickness:	1.5 to 3 D_{50}
•Coefficient of Uniformity:	1.2 to 4.0

B-18

Limited Overtopping, Embankment Breach and Discharge

Issues, Resolutions & Research Needs Related to Dam Failure Analysis: Oklahoma Workshop, June 26-28, 2001

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ABSTRACT

Over 10,000 flood control reservoirs constructed with the assistance of the USDA provide almost $1 billion in benefits each year. Sixty-two percent of these 10,000 structures will reach age 50 by 2020. As these structures age additional trapped sediment may reduce the flood control capacity of the reservoir, population increases and changes in land in the upstream watershed may result in increased runoff, population encroachment on the downstream channels may result in structures that were designed to protect agricultural land now being depended upon to protect lives and homes, and many state dam safety regulatory requirements have also been increased since the original construction as a result of federal legislation and/or state laws. Because of this, public safety requires that this aging infrastructure be re-evaluated and, in some cases, rehabilitated. A key aspect of this re-evaluation is prediction of the performance of existing hydraulic structures and channels during extreme flood events that may exceed original design conditions. This includes prediction of allowable overtopping, rate of embankment breach and failure, and resulting discharge.

INTRODUCTION

The drought of the 1930's, followed by flooding in the 1940's, made the U.S. agriculture community keenly aware of the need to keep the water and soil in place. Following World War II, numerous management practices to control erosion and reduce flooding were implemented with the assistance of the USDA. Included were the upland flood control structures constructed under PL-534, PL-566, Pilot, and RC&D watershed programs. Approximately $14 billion was invested in more than 10,000 structures that presently provide on the order of $1 billion in benefits annually. These flood control structures have become an integral part or the nation's transportation and communications infrastructure through their protection of roadways, pipelines, etc.

As these structures continue to age, additional trapped sediment may reduce the flood control capacity of many of these reservoirs. Population increases and changes in land use have modified the hydrologic properties of the watersheds upstream of some of these structures, resulting in increased runoff of water and/or sediment from a given storm. Increasing population and encroachment on the downstream channels have resulted in structures that were designed to protect agricultural land now being depended upon to protect lives and homes. Many state dam safety regulatory requirements have also been increased since the original construction as a result of federal legislation and/or state laws. Essentially all of the state dam safety laws were written or significantly revised after dam safety concerns were raised in the 1970's following the failure of Teton and Tacoa Falls Dams. Over 70% of USDA-assisted projects were in place by that time. Conflicts between the design of the older dams and the new dam safety rules are inevitable. Public safety requires that the aging infrastructure that includes these dams be re-evaluated and, in some cases, the dams rehabilitated and/or modified if they are to continue to serve public needs.

The Hydraulic Engineering Research Unit of the ARS Plant Science and Water Conservation Research Laboratory is conducting research to address the problems associated with rehabilitation of the watershed flood control structures and channels, and identified as research objectives. Key identified knowledge deficiencies related to rehabilitation of watershed flood control structures and channels may be expressed in the form of research objectives as: 1) determination of the extent of overtopping that may be sustained by a vegetated earth embankment, such as a dam, without resulting in embankment breach, and 2) quantification of the processes associated with breach such that timing, rate, and geometry of breach may be predicted, and 3) quantification of the discharge hydrograph and peak discharge as a result of an embankment breach. The results of this research will be incorporated into evaluation tools and software, design criteria, and management practices that will allow the continued service and increased benefit of the nation's agricultural watershed flood control infrastructure.

EARTH EMBANKMENT EROSION RESEARCH

Although the detailed data on embankment overtopping have been very limited, substantial data have been gathered from vegetated spillways, which have experienced flood flows. Analyses of these data, combined with laboratory tests and analyses, have led to the development of a procedure for evaluation of earth spillway performance (NRCS, 1997). The model used in this procedure divides the erosion process into three phases. These phases are: 1) the failure of the vegetal cover, if any, and the development of concentrated flow, 2) erosion in the area of concentrated flow leading to the formation of a vertical or near vertical headcut, and 3) the upstream advance of the headcut leading to breach which may also be accompanied by further widening and deepening. The three phases describing progressive spillway erosion have also been observed for erosion of overtopped earth embankments when the embankment material exhibits even a small amount of cohesion (Hanson et al 2001). Therefore, even though caution is appropriate in attempting to extend this model directly to prediction of embankment breach, the breakdown of the process into these same three phases would be appropriate. Because of the short distance through the crest or an embankment dam, the concept of allowable overtopping is practically limited to the first two phases.

Tests have been conducted to evaluate the effectiveness of un-reinforced vegetation for overtopping protection and the applicability, on steep slopes, of the analysis tools of the first two phases of the three phase spillway model (Temple and Hanson, 1998; Hanson and Temple, 2001). It was found that the vegetation could provide substantial protection and that the relations used for phase 1 and phase 2 erosion of spillways could be effectively applied to the steeper embankment slopes. Differences observed were associated primarily with the reduced flow depth on the steeper slopes. This reduction in flow depth reduced the interaction of the vegetal elements with the turbulent flow field as a result of the turbulent scales being less than the length of the individual elements. However the effect of this on the flow resistance or protective action of the grass appeared to be minor. It was also observed that the decrease in flow depth emphasized the effects of discontinuities in the cover or surface. The importance of this effect on predicting breach or time to breach is shown by the curves of Figure 1 (reproduced from Temple and Hanson, 2001).

The equations used in the development of the curves of Figure 1are those documented in NRCS (1997) for the limits of phase 1, vegetal, failure. All curves are based on computations for a 3:1 embankment slope. Curve a represents a very high quality bermudagrass cover over a soil having a plasticity index of 15. Curve b is for that same condition except that the cover or surface exhibits minor discontinuities. A minor discontinuity is one that is large enough for the turbulent flow to directly impact the erodible material, but small enough that the flow does not concentrate within the discontinuity. This would normally imply a maximum dimension of the discontinuity parallel to flow on the order of flow depth and/or stem length. Curve d is for the same condition except that the discontinuity is large enough to allow the flow to fully concentrate, thereby negating any protective effect of the vegetal cover. Curve c is added to illustrate the relative importance of the material erodibility. Conditions for curve c are the same as for curve b except that the plasticity index of the material is reduced to zero to represent a highly erodible condition. The effect is substantially less than that indicated by adding discontinuities to the cover or surface. In all cases the curves represent failure on the slope and do not address the effects of the impacts of high velocity flow on toe or berm areas. Figure 1 illustrates that un-reinforced vegetation may be effective in providing overtopping protection, but attention must be given to maintenance.

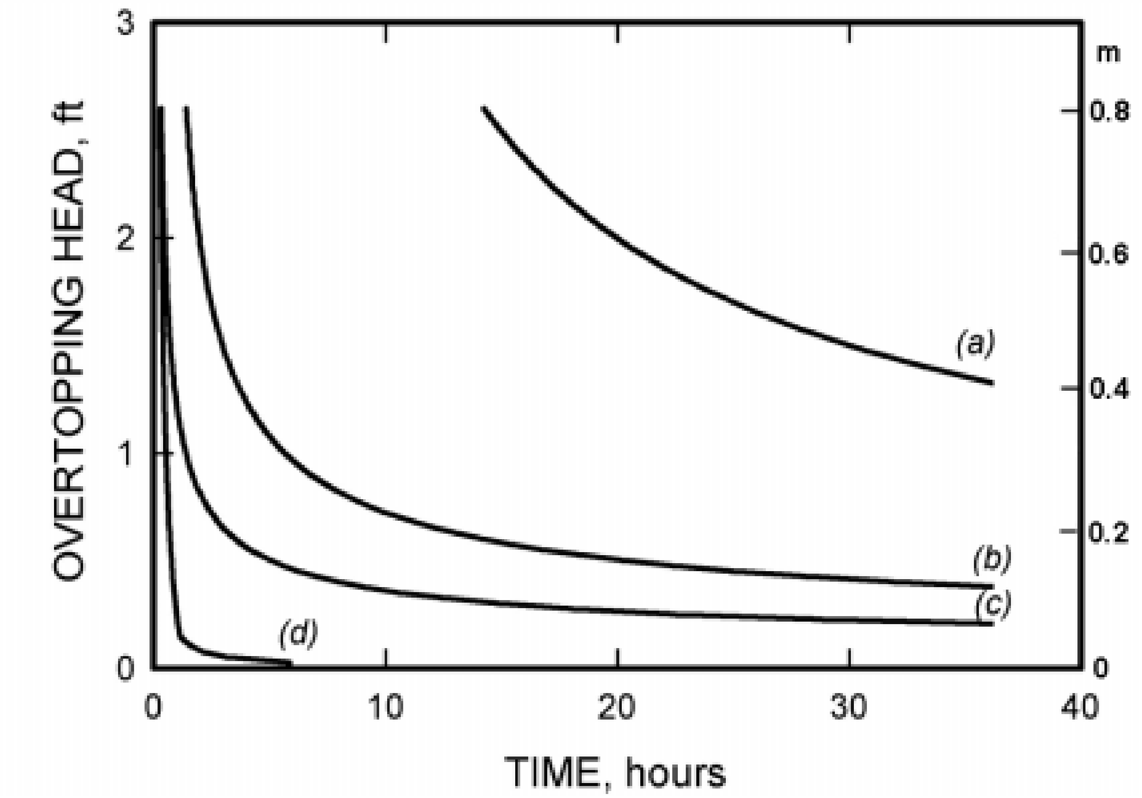

Figure 1. Potential allowable embankment overtopping based on the point of vegetal cover failure for: (a) a good cover of bermudagrass and a material plasticity index of 15; (b) a grass cover with minor surface discontinuities and a material plasticity index of 15; (c) a grass cover with minor surface discontinuities and a material plasticity index of 0; and (d) a grass cover with major discontinuities and a material plasticity index of 15.

For homogeneous earth embankments, phase 2, concentrated flow erosion, will usually represent only a very brief portion of the hydrograph. The combination high stresses and low flow depth on the steep embankment slope means that once the flow becomes concentrated in the developing discontinuity, erosion to the point of development of a vertical or near vertical headcut is normally quite rapid. This phase received some attention in the research conducted on steep slopes (Hanson and Temple 2001) and embankment overtopping (Hanson et al 2001). These tests verified that phase 2 is typically very brief and that the relations used in the spillway model are adequate. An important point that was brought out in Hanson and Temple 2001 is that erodibility of any given soil may vary several orders of magnitude depending on compaction density, and moisture content (Figure 2); indicating that proper measurement of erodibility is essential in predicting embankment performance. Erodibility is typically defined by two soil parameters, critical stress τ_c and the detachment coefficient k_d. The erosion is assumed not to begin until the effective hydraulic stress τ_e exceeds τ_c. Once the critical stress is exceeded the rate of erosion, $d\varepsilon/dt$ is assumed to occur at a linear rate described by the excess stress equation:

$$\frac{d\varepsilon}{dt} = k_d(\tau_e - \tau_c) \qquad [1]$$

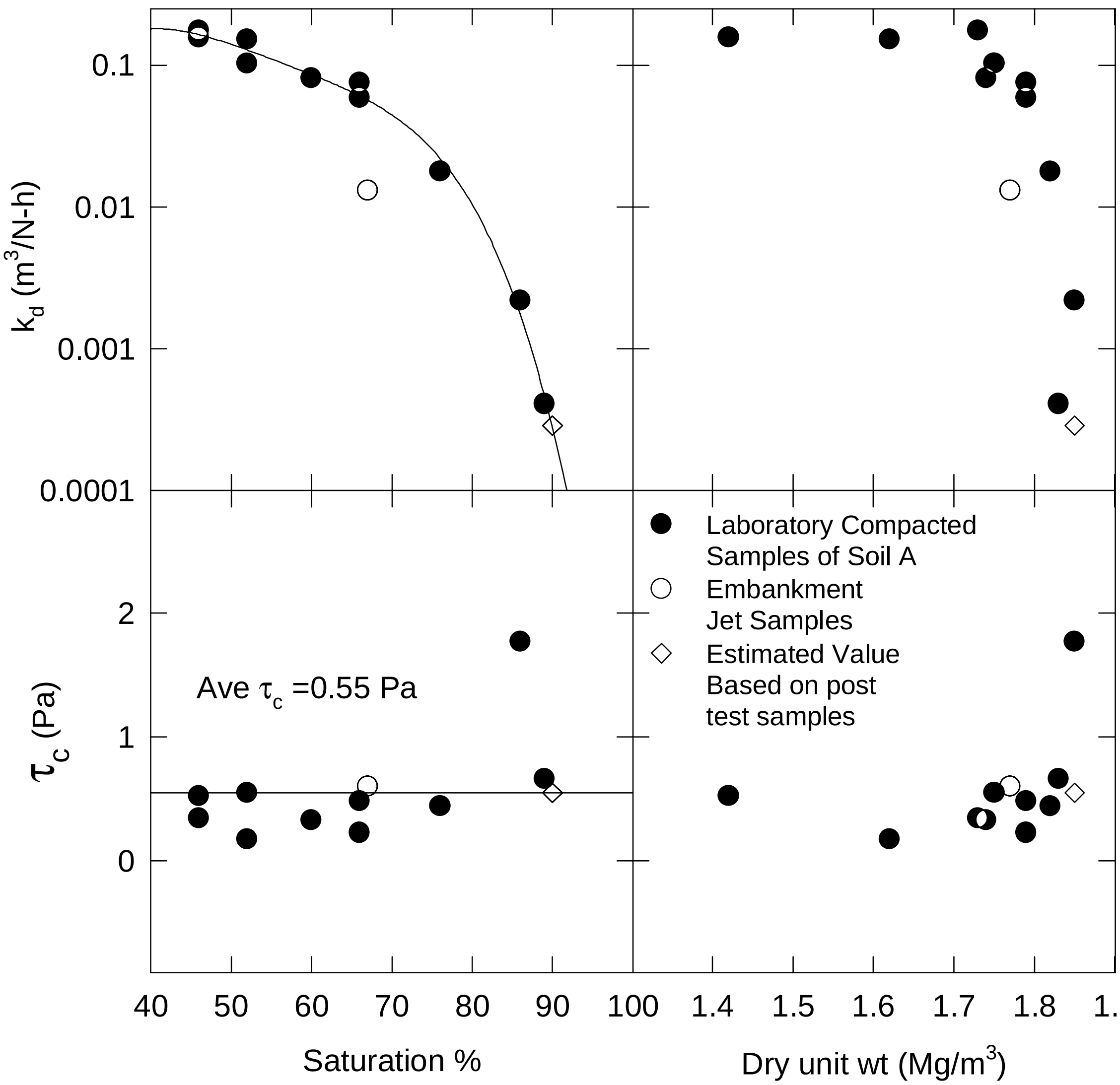

Figure 2. Relationship of a) k_d and saturation, b) k_d and dry unit weight, c) τ_c and saturation, and d) τ_c and dry unit weight for laboratory jet tests, and embankment jet tests.

Phase 3, headcut deepening and advance, is a critical part of the breaching process. The purpose of the spillway model is the determination of the potential for breach to occur. Although this is an important consideration for overtopped embankments, the time of breach and the outflow from the breach are also important considerations. This means that a two-dimensional model (width of eroded area not considered) is not adequate, and erosion following the initial breach needs to be considered. This will require the addition of a model component to track headcut width during breach development and the quantification of at least two additional phases. These additional phases are the downward erosion of the crest of the vertical following submergence of the headcut and the widening of the headcut following complete local removal of the embankment in the vicinity of the breach. Research presently underway includes breaching of embankments such as that shown in Figure 3, and will assist in quantifying the action that occurs during these additional phases. Laboratory tests confirm that material properties may have a major impact on the rate of headcut advance, and therefore time to breach and breach rate. The headcut erodibility index based relations used in the spillway erosion model are semi-empirical and were developed to cover a broad range of geologic conditions. They were also developed without consideration of such things as pore water changes with position of the headcut. Therefore, as discussed by Hanson et al 2001, it should be possible to either refine the relations for application to embankment conditions or to replace this approach with an alternate. Work is continuing in this area. The focus to date has been on homogeneous embankments, but plans are being made to expand the testing program to include other types.

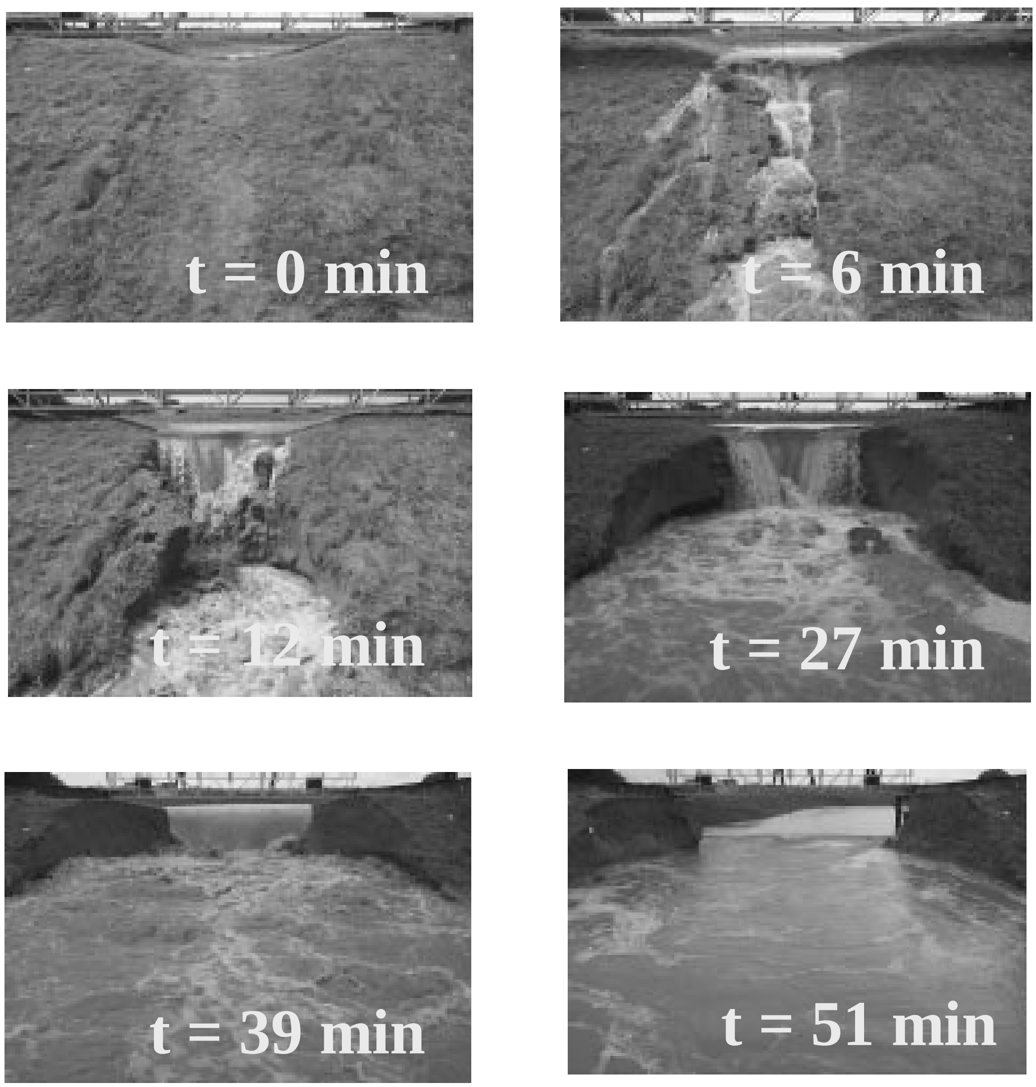

Figure 3. Time series of an embankment breach test of a homogeneous non-plastic sandy soil conducted at the ARS Hydraulic Laboratory, Stillwater, OK.

SUMMARY

Research efforts at the ARS Plant Science and Water Conservation Research Laboratory have resulted in an increased understanding of the erosion processes applicable to an overtopped earth embankment. Advances in predicting performance of vegetated earth spillways form a point of beginning for quantifying the breach process for embankments in a fashion that includes prediction of the extent of overtopping that may occur without breach, and the time of breach when breach does occur. However, the present spillway model is not considered adequate for this application.

Additional research is being conducted to allow existing erosion models to be refined and extended. With respect to the earth spillway erosion model discussed, this involves refinement of existing headcut erosion components and development of additional components to address the latter stages of breach development, breach widening and breach discharge prediction. Research presently underway will contribute to development of these components.

Research on the ability of un-reinforced vegetation to protect embankment faces has shown that grass can substantially increase the time to breach. However, taking advantage of this capability will require that attention be given to maintenance of the cover and to protecting areas of concentrated attack such as the slope toe.

Although the research described in this paper focuses on the performance of smaller dams of the type constructed with the assistance of the United States Department of Agriculture, the results may also be used to better understand the response of larger earth dams and will compliment results of research on breach of large dams such as that being carried out under the CADAM project (European Commission, 1998a, 1998b, 1999a, 1999b, 2000). This report discusses the approach being used in USDA research, some of the key underlying physical processes that must be considered, and the progress being made.

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B-19

HEC Models for Dam Break Flood Routing

by

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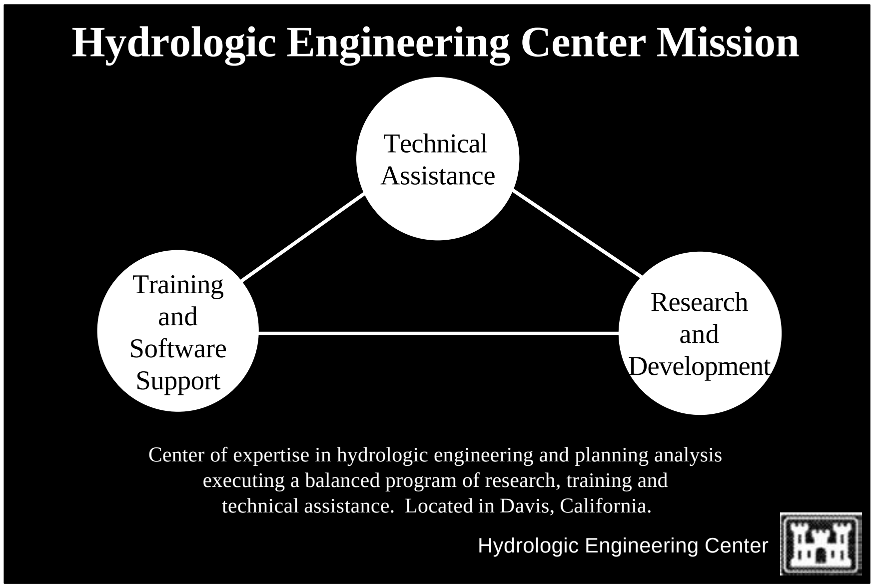

HEC Products

- Hydrologic engineering software; Corps, Public, International
- Technical Methods and Guidance
- Technical Assistance
- Prototype studies, Research and Applications
- Training Courses, Workshops and Seminars

Some HEC History

- **80's** - Simplified techniques, test routing methods
- **90's**
  - NexGen HEC-RAS development for 1-D steady flow
  - UNET (Mississippi Basin Modeling System for forecasting)
  - R & U (Alamo Dam, used combination of DAMBRK & HEC-RAS
- **2000's**
  - HEC-RAS (unsteady flow)
  - CWMS (Corp Water Management System)

References

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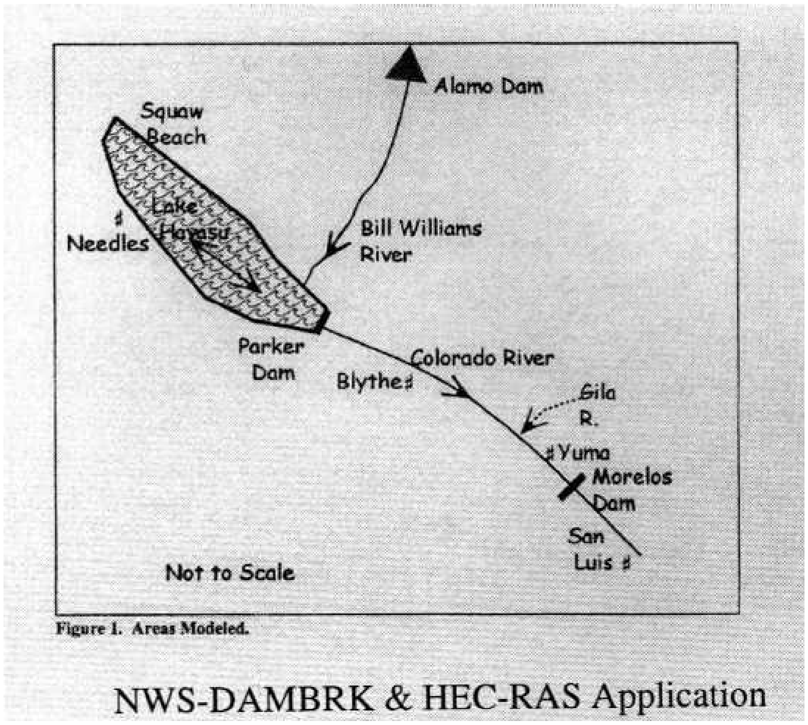
In the early '80's HEC looked at using the TVA explicit model for unsteady flow applications. At that time, a geometric pre-processing program (GEDA) was developed to compute data tables of geometric properties for USTFLO from HEC-2 format cross-sections. This capability was later expanded to prepare DAMBRK and DWOPER geometric data from HEC-2 cross sections. Research was conducted regarding selection of appropriate flood routing procedures (HEC, 1980a) and generalized solutions to dam break flood routing (HEC, 1980b).

UNET (HEC, 2001) has been routinely utilized throughout the Corps for 1-D unsteady flow modeling for at least the last fifteen years. Many features have been developed by Dr. Barkau for local needs (HEC, 1998). Of particular interest and continuing research are issues related to calibration - both hydrology related (what is the real flow hydrograph) and hydraulics related (what is the appropriate roughness function for the observed stage hydrograph and input flow hydrograph). Major developments to UNET (levee breach connections to off-channel storage areas, etc.) were prompted by large floods in the Mississippi-Missouri system in '93.

Current HEC work involves incorporation of the UNET unsteady flow equation solver into HEC-RAS. This allows the more complete geometric description of the river used by RAS to be used as well as RAS' graphical displays and data editing capabilities. RAS unsteady flow modeling will support the Corps Water Management System (HEC, 2000b).



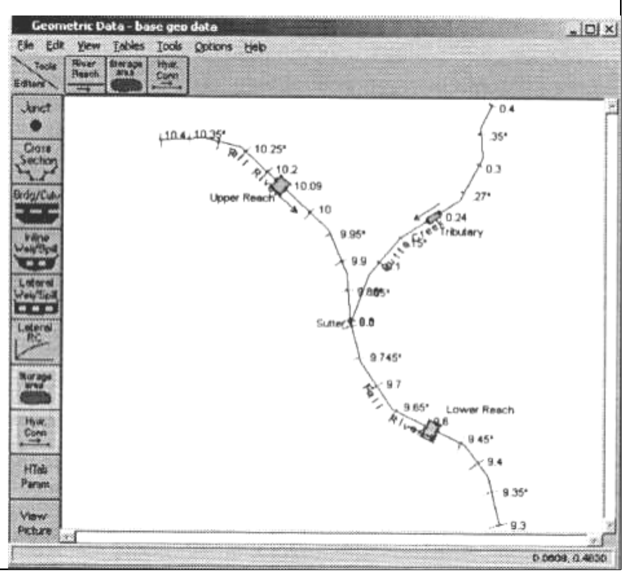
Schematic of the Alamo Dam study area. A DAMBRK model had been developed of this system by the Seattle Dist. Of the Corps (for the L.A. Dist.). This model was used to evaluate additional failure scenarios. The DAMBRK cross sections were converted into RAS sections so that overbank depths and velocities could be computed. RAS was run as a steady flow model using peak flows at each section computed by DAMBRK (RAC, 1999).

Steps to Develop RAS Data

- Start a New Project
- Enter Geometric data
- Enter Flow and Boundary data
- Establish a Plan and Run
- Evaluate model results
- Adjust model, as necessary

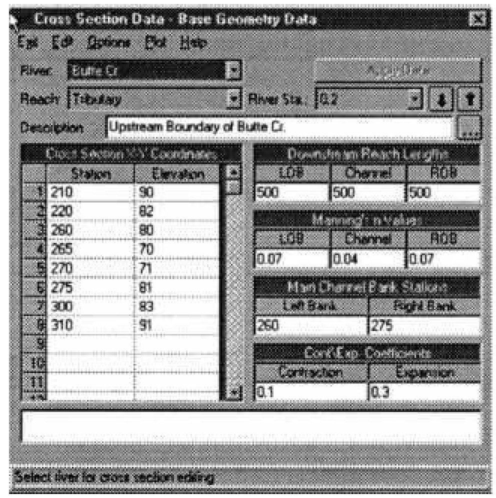
HEC-RAS Geometric Data

- River
- Reach
- Junctions
- River Stations
  - Cross section data entry



Cross-section Data Editor

- Option: Add Section
- River-Reach-Station
- Input section data
  - Station/Elevation Data
  - Reach lengths
  - Manning's *n*
  - Bank Stations
  - Contract/Expand Coef.



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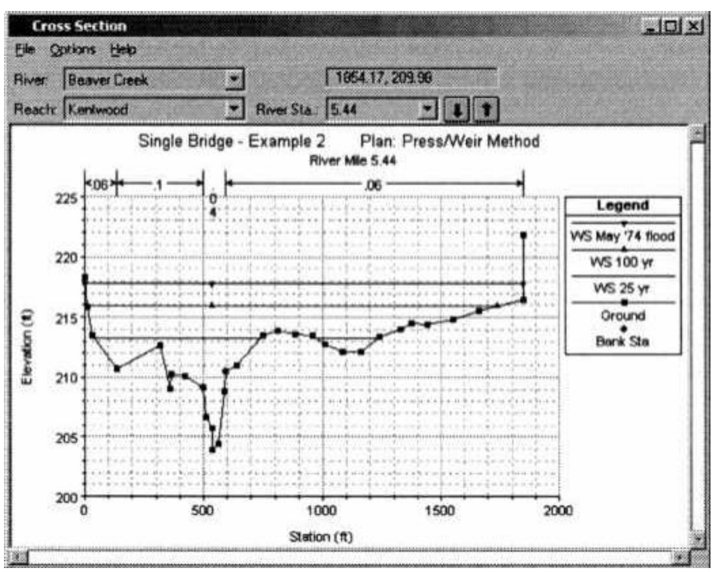
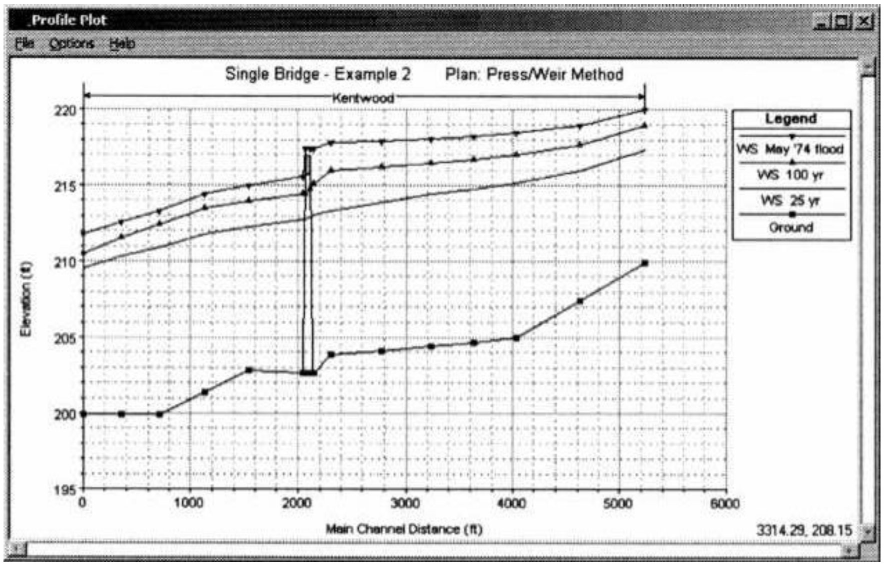
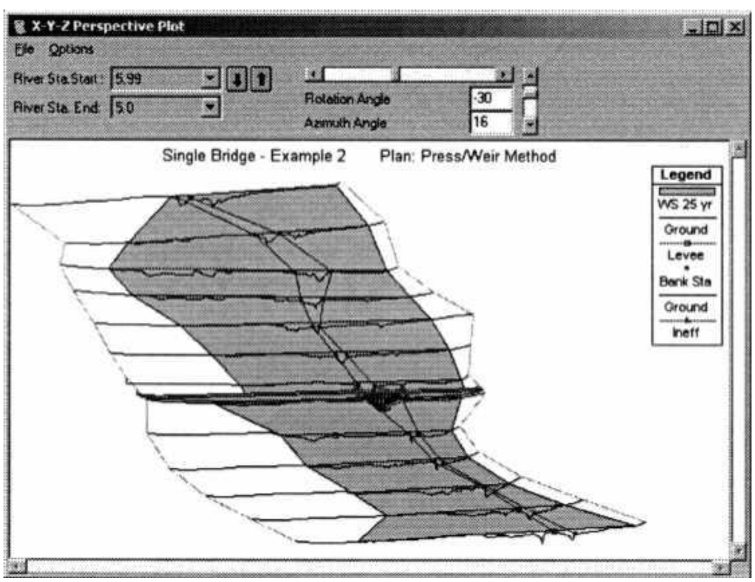
Cross-section Plot



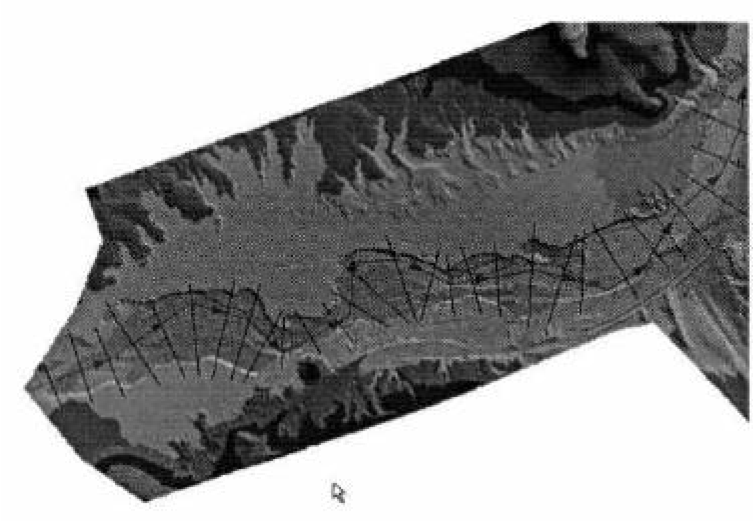
Profile Plot



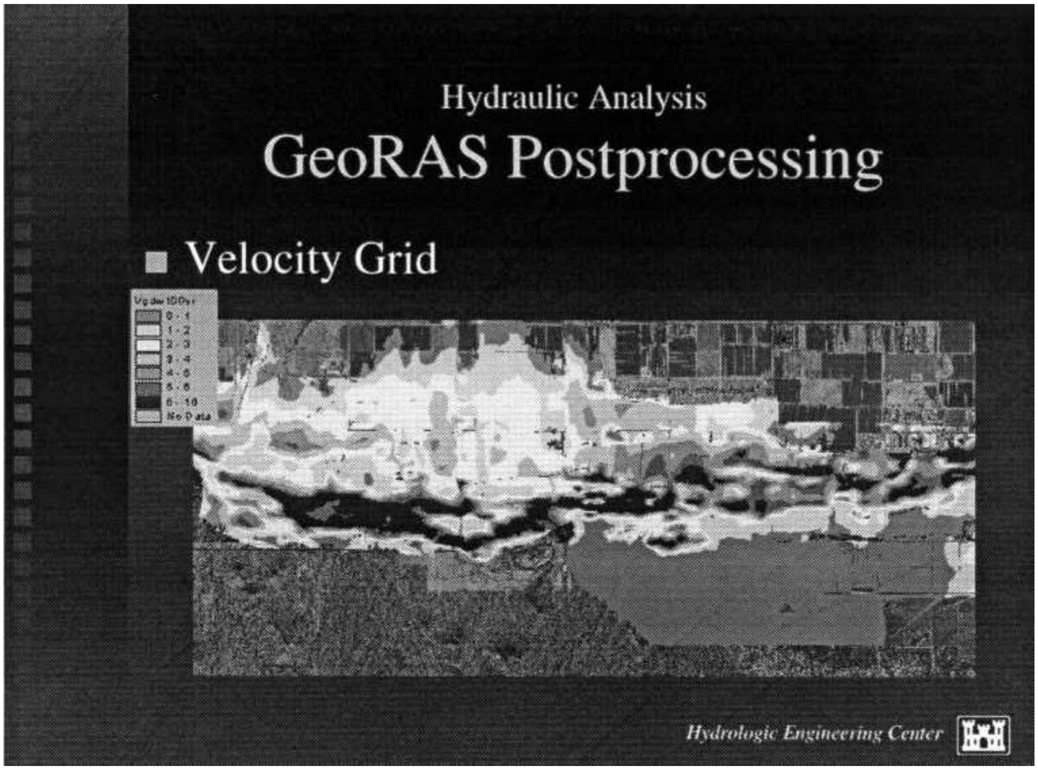
XYZ Perspective Plot



Use of GIS/DEM data



RAS cross section data can be developed from a digital terrain model using HEC-GeoRAS, which is an extension to ArcView (HEC, 2000a). This figure illustrates how the stream centerline and cross section strike lines are chosen by the user. This example is Las Vegas Wash.



Results of HEC-RAS computations can be viewed using the GIS/DEM data representation that was used to construct input data. The results that can be displayed (mapped) include traditional inundated areas for flows modeled as well as depth and velocity distributions. Ongoing work to extend HEC-RAS for sediment transport analysis will utilize this information to compute and display transverse distributions of bed shear stress and stream power (based upon the local grain size). This example is the Salt River near Phoenix, AZ.

RAS Unsteady Flow

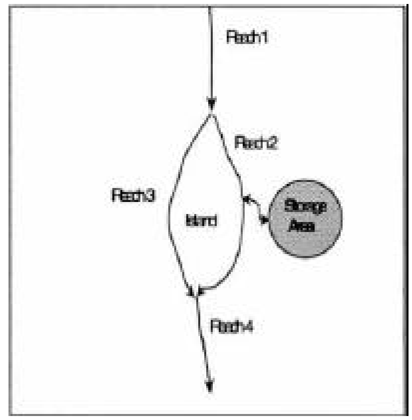
- Overview
- New Geometric Features for RAS 3.0
- Geometric pre-processor
- Boundary and initial conditions
- Unsteady flow simulation manager
- Post-processor
- Additional graphics/tables to view results

Overview

- Common geometry and hydraulic computations for steady & unsteady flow
- Using the UNET equation solver (Dr. Robert Barkau)
- Can handle simple dendritic streams to complex networks
- Able to handle a wide variety of hydraulic structures
- Extremely fast matrix solver

New Geometric Features for HEC-RAS

- Existing Geometric Features all work for unsteady flow (XS, bridges, Culverts, inline weirs/spillways)
- Lateral Weirs/Spillways
- Storage Areas
- Hydraulic Connections (weirs, gated spillways, and culverts)



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All of the existing hydraulic analysis features in the previous steady flow versions of HEC-RAS work within the new unsteady flow computation. The following new features were added to work with unsteady flow, but they also work in the steady flow simulation:

• Lateral weirs/gated spillways.

• Storage areas: used to model areas of ponded water.

• Hydraulic connections: use to exchange water between storage areas, storage areas and a river reach, and between different river reaches.

Pre-processing Geometry

- For unsteady flow, geometry is pre-processed into tables and rating curves
  - **Cross sections** are processed into tables of area, conveyance, and storage
  - **Bridges and culverts** are processed into a family of rating curves for each structure
  - **Weirs and gated structures** are calculated on the fly during unsteady flow calculations
  - Pre-processor **results can be viewed** in graphs and tables

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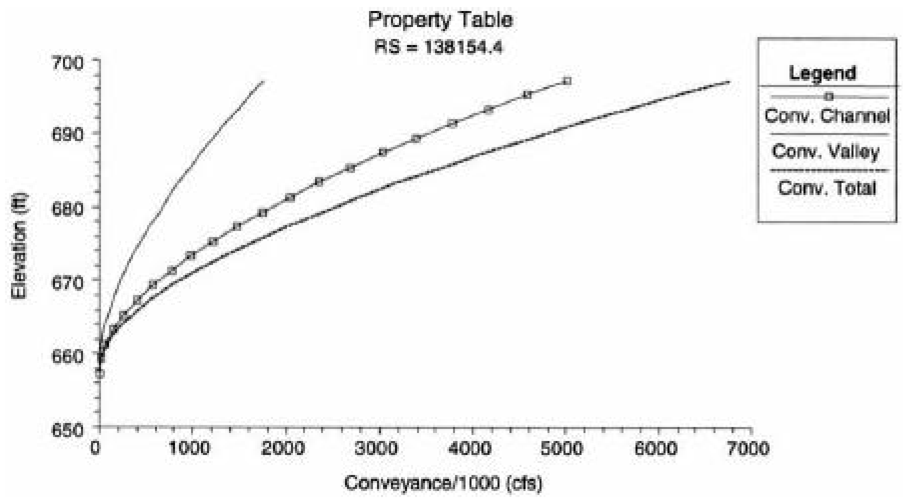
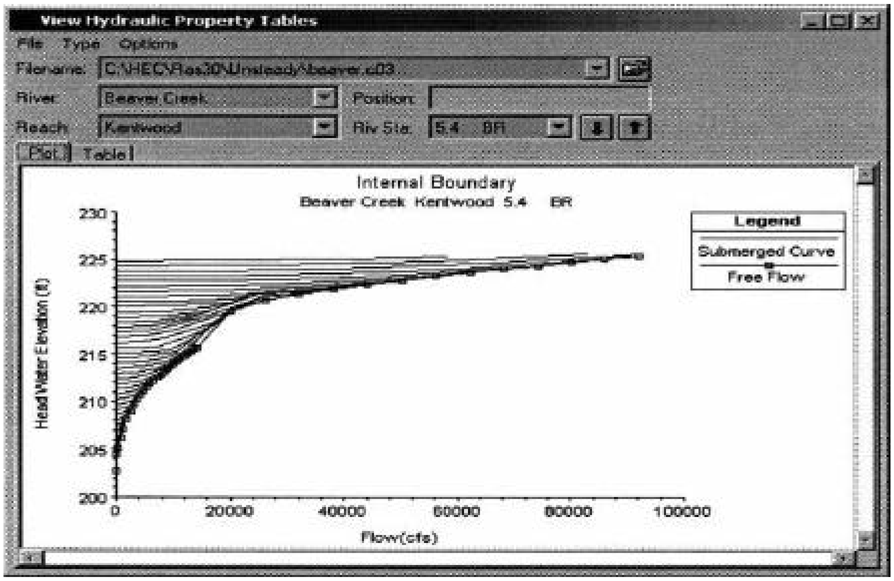
The pre-processor is used to process the geometric data into a series of hydraulic properties tables and rating curves. This is done in order to speed up the unsteady flow calculations. Instead of calculating hydraulic variables for each cross-section during each iteration, the program interpolates the hydraulic variables from the tables. **The pre-processor must be executed at least once, but then only needs to be re-executed if something in the geometric data has changed.**

Cross Section Properties Plot



Cross sections are processed into tables of elevation versus hydraulic properties of areas, conveyances, and storage. Each table contains a minimum of 21 points (a zero point at the invert and 20 computed values). The user is required to set an interval to be used for spacing the points in the cross section tables. The interval can be the same for all cross sections or it can vary from cross section to cross section. This interval is very important, in that it will define the limits of the table that is built for each cross section. On one hand, the interval must be large enough to encompass the full range of stages that may be incurred during the unsteady flow simulations. On the other hand, if the interval is too large, the tables will not have enough detail to accurately depict changes in area, conveyance, and storage with respect to elevation.

Bridge Hydraulic Properties Plot



Hydraulic structures, such as bridges and culverts, are converted into families of rating curves that describe the structure as a function of tailwater, flow and headwater. The user can set several parameters that can be used in defining the curves.

Boundary and Initial Conditions

- Boundary conditions must be established at all ends of the river system:
  - Flow hydrograph
  - Stage hydrograph
  - Flow and stage hydrograph
  - Rating curve
  - Normal depth

The user is required to enter boundary conditions at all of the external boundaries of the system, as well as any desired internal locations, and set the initial flow and storage area conditions in the system at the beginning of the simulation period.

Boundary and Initial Conditions

- Interior boundary conditions can also be defined within the river system:
  - Lateral inflow to a node
  - Uniform lateral inflow across a reach
  - Ground water inflow
  - Time series of gate openings
  - Elevation controlled gate
  - Observed internal stage and/or flow hydrograph

Unsteady Flow Simulation Manager

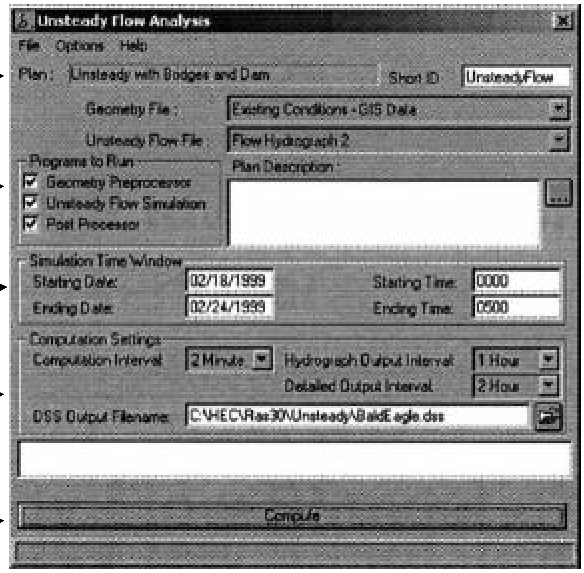
1. Define a Plan

2. Select which programs to run

3. Enter a starting and ending date and time

4. Set the computation settings

5. Press the Compute button



Once all of the geometry and unsteady flow data have been entered, the user can begin performing the unsteady flow calculations. To run the simulation, go to the HEC-RAS main window and select **Unsteady Flow Analysis** from the **Run** menu.

The unsteady flow computations within HEC-RAS are performed by a modified version of UNET (HEC, 2001). The unsteady flow simulation is actually a three step process. First a program called RDSS (Read DSS data) runs. This software reads data from a HEC-DSS file and converts it into the user specified computation interval. Next, the UNET program runs. This software reads the hydraulic properties tables computed by the preprocessor, as well as the boundary conditions and flow data from the interface and the RDSS program. The program then performs the unsteady flow calculations. The final step is a program called TABLE. This software takes the results from the UNET unsteady flow run and writes them to a HEC-DSS file.

Post-processing Results

- Used to compute detailed hydraulic information for a set of user-specified times and an overall maximum water surface profile.
- Computed stages and flows are passed to the steady flow program for the computation of detailed hydraulic results

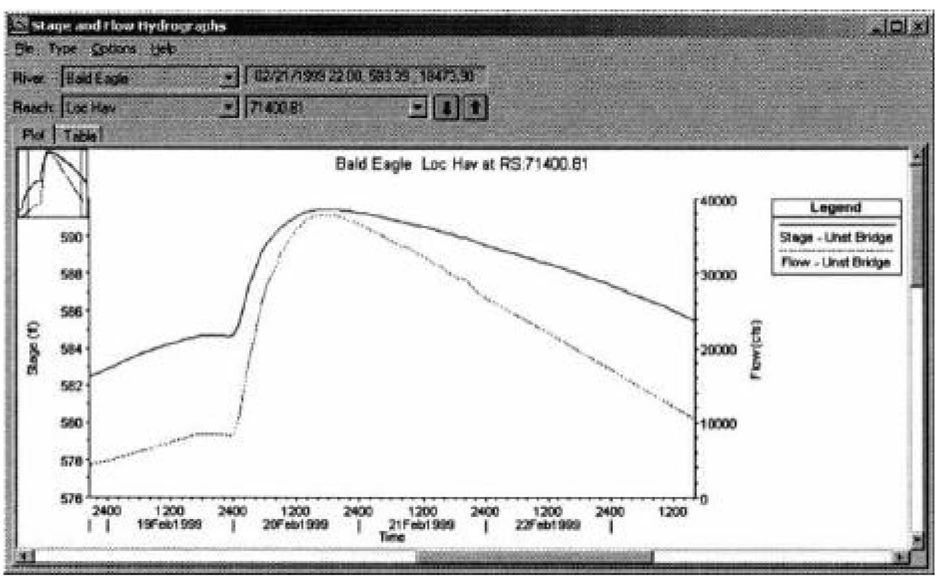
The Post Processor is used to compute detailed hydraulic information for a set of user specified time lines during the unsteady flow simulation period. In general, the UNET program only computes stage and flow hydrographs at user specified locations. **If the Post Processor is not run, then the user will only be able to view the stage and flow hydrographs and no other output from HEC-RAS**. By running the Post Processor, the user will have all of the available plots and tables for unsteady flow that HEC-RAS normally produces for steady flow.

When the Post-Processor runs, the program reads from HEC-DSS the maximum water surface profile (stages and flows) and the instantaneous profiles. These computed stages and flow are sent to the HEC-RAS steady flow computation program SNET. Because the stages are already computed, the SNET program does not need to calculate a stage, but it does calculate all of the hydraulic variables that are normally computed. This consists of over two hundred hydraulic variables that are computed at each cross section for each flow and stage.

Viewing Unsteady Flow Results

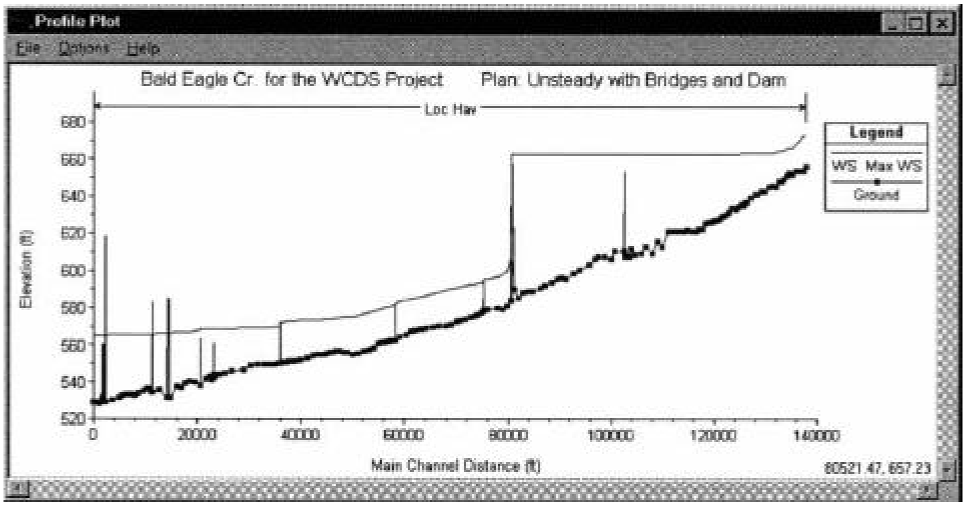
- All of the output that was available for steady flow computations is available for unsteady flow (cross sections, profile, and perspective plots and tables).
- Stage and flow hydrographs
- Time series tables
- Animation of cross section, profile and perspective graphs

Stage and Flow Hydrographs



The stage and flow hydrograph plotter allows the user to plot flow hydrographs, stage hydrographs, or both simultaneously. Additionally, if the user has observed hydrograph data, that can also be plotted at the same time. The plot can be printed or sent to the windows clipboard for use in other software.

Animation of Profile Plot



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The HEC-RAS software has the ability to animate the cross section profile. When the user selects Animation, the plot steps thought the computed results in a timed sequence. The user can control the speed of the animation, as well as step through individual time steps.

Application of HEC-RAS to a Dam Break Situation

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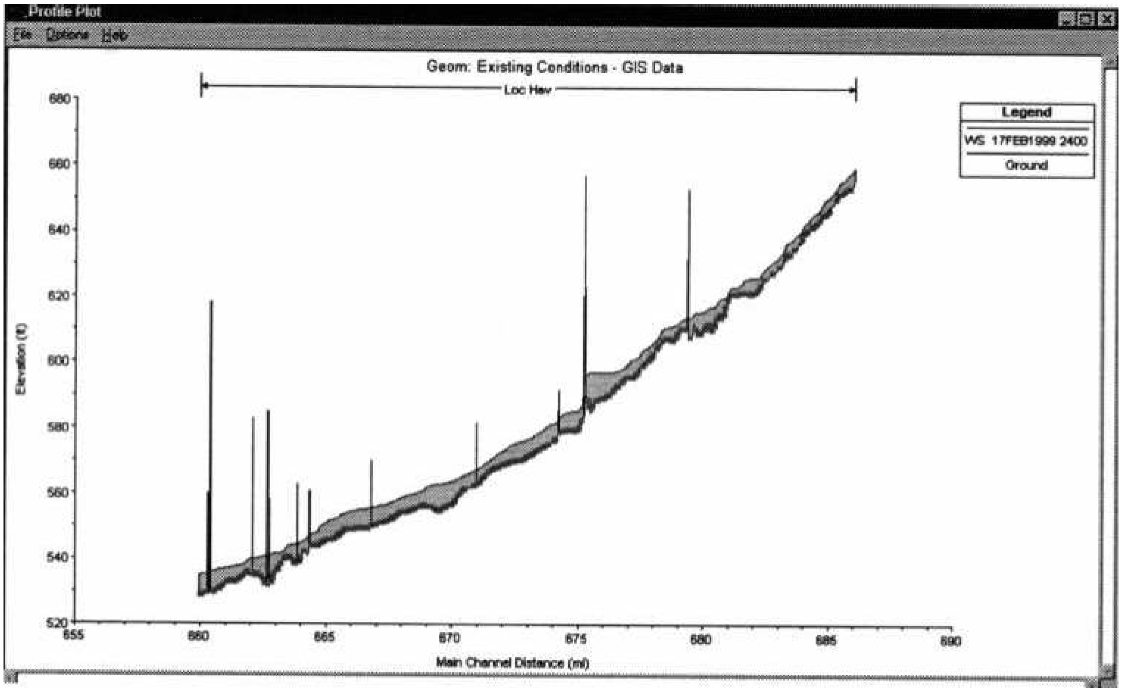
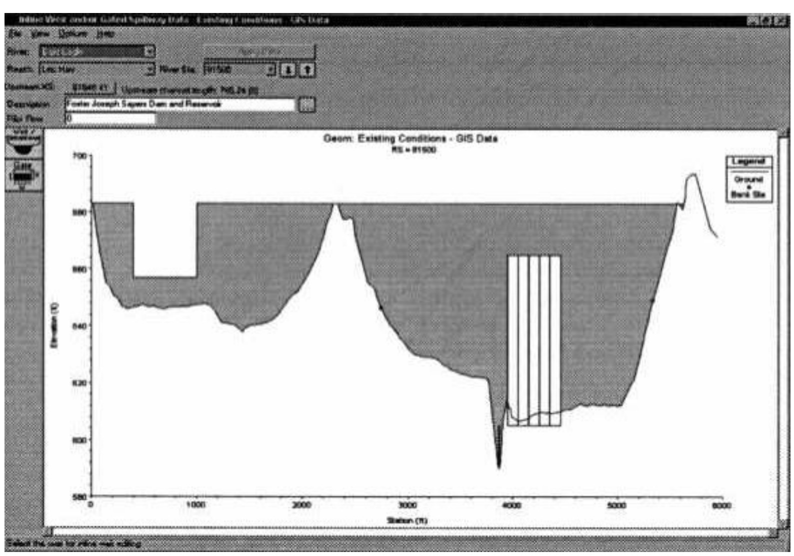
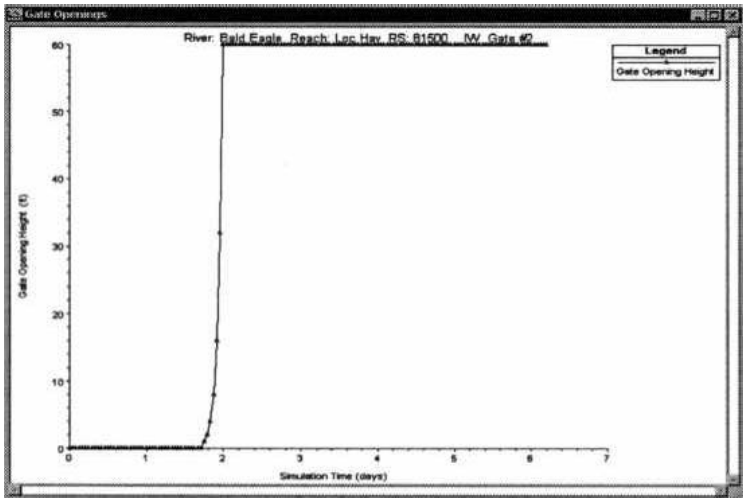
HEC-RAS (or UNET) can be used to simulate the unsteady routing of flood hydrographs resulting from breaching of dams or levees. The user has many methods available within the programs to generate the hydrographs. In this example, a gate operation is used to mimic the failure of a dam embankment. UNET has the ability to compute flows through levee and embankment breaches.



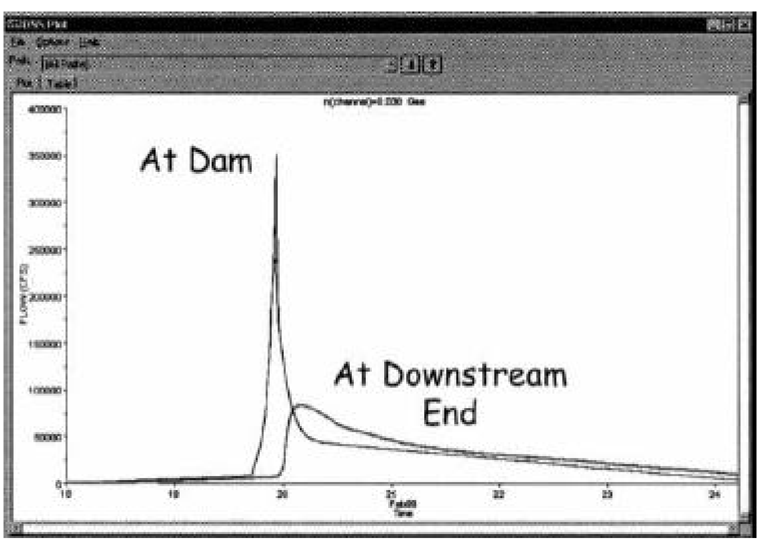
Gate Section



Gate Operation



Computed Hydrographs



Future Work

- Dam & Levee Breaching
  - Overtopping
    - Initiation via
      - Water surface elevation
      - Clock (simulation) time
    - Growth rate
      - Linear
      - Exponential
    - Use weir equations with submergence

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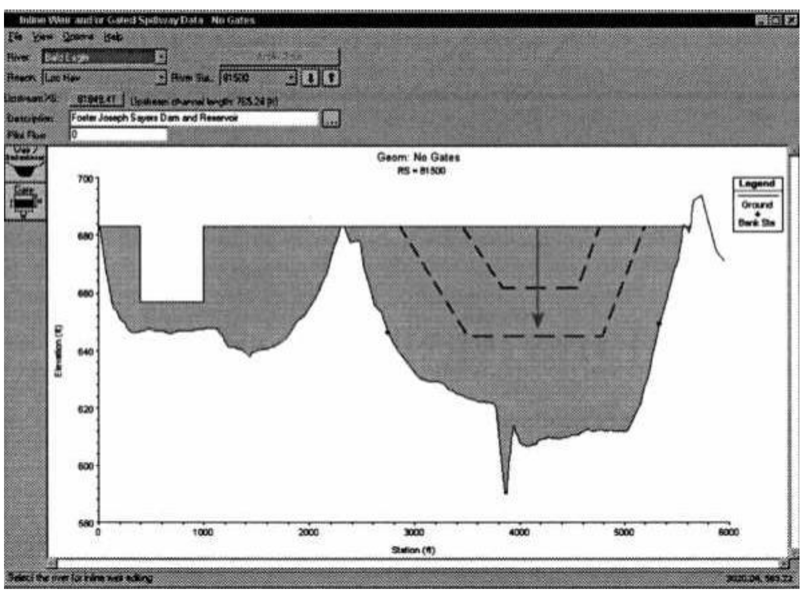
Weir Type Breach



Future Work (cont.)

- Dam & Levee Breaching
  - Piping
    - Initiation via
      - Water surface elevation
      - Clock (simulation) time
    - Progression
      - Box until top collapses (when top elev. > W.S.)
    - Orifice flow transitioning to weir flow

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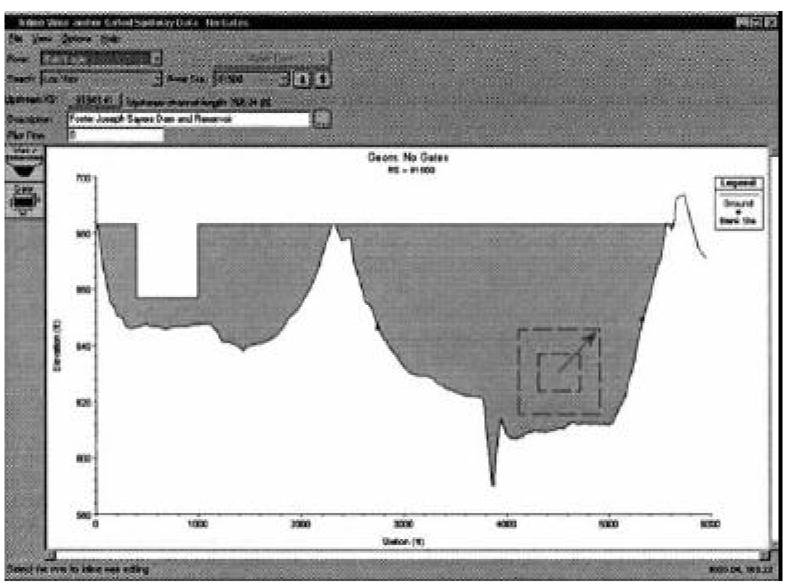
Piping Type Breach



Product Availability

- Internal testing (Teton, MBMS etc.) this summer
- General release of HEC-RAS 3.1 - Fall of 2001
- Same breaching algorithms to be used in HEC-HMS

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B-20

CADAM & IMPACT: European Research Projects Investigating Dambreak Modelling and Extreme Flood Processes

Issues, Resolutions & Research Needs Related to Dam Failure Analysis: Oklahoma Workshop, June 26-28, 2001

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SYNOPSIS
This paper provides an overview of the CADAM Concerted Action project, which was completed in January 2000, and an introduction to the IMPACT research project which will commence November / December 2001. Both projects have been funded by the European Commission, with the IMPACT project addressing key research issues identified during the CADAM concerted action project.

The *Concerted Action project on Dambreak Modelling* (*CADAM)* involved participants from 10 different countries across Europe and ran between Feb 98 and. Jan 2000. The aim of the project was to review dambreak modelling codes and practice from first principles through to application, to try and identify modelling best practice, effectiveness of codes and research needs. Topics covered included the analysis and modelling of flood wave propagation, breaching of embankments and dambreak sediment effects. The programme of study was such that the performance of modelling codes were compared against progressively more complex conditions from simple flume tests through physical models of real valleys and finally to a real dam-break test case (the Malpasset failure). The study conclusions are presented in a final project report, published by both the EC and the IAHR. This paper provides a brief summary of the key issues identified.

The IMPACT project *(Investigation of Extreme Flood Processes & Uncertainty)* focuses research in a number of key areas that were identified during the CADAM project as contributing greatly to uncertainty in dambreak and extreme flood predictions. Research areas include embankment breach (formation and location), flood propagation (infrastructure interaction and urban flooding) and sediment movement (near and far zones with respect to embankment failure). The uncertainty associated with current predictive models and following project research will be demonstrated through application to case study material. Implications of prediction uncertainty for end users with applications such as asset management and emergency planning will also be investigated.

CADAM – AN INTRODUCTION

The first legislation in Europe for dam-break risk analysis was presented in France in 1968, following the 1959 Malpasset dam-break that was responsible for more than 400 injuries. Since then, and especially more recently, many European countries have established legal requirements. However the techniques applied when undertaking the specified work can vary greatly. The perception of risks related to natural or industrial disasters has also evolved, leading to public demand for higher standards of safety and risk assessment studies. Considering the relatively high mean population density within Europe, a dam-break incident could result in considerable injury and damage; efficient emergency planning is therefore essential to avoid or minimise potential impacts.

Dam-break analyses therefore play an essential role when considering reservoir safety, both for developing emergency plans for existing structures and in focussing planning issues for new ones. The rapid and continuing development of computing power and techniques during the last 15 years has allowed significant advances in the numerical modelling techniques that may be applied to dam-break analysis.

CADAM was funded by the European Commission as a Concerted Action Programme that ran for a period of two years from February 1998. Under these terms, funding was provided only to pay for travel and subsistence costs for meetings, and for project co-ordination. All work undertaken during the study was therefore achieved through the integration of existing university and national research projects. HR Wallingford co-ordinated the project, with additional financial support from the DETR.

The project continued work started by the IAHR Working Group (established by Alain Petitjean following the IAHR Congress in 1995) and had the following aims:

- The exchange of dam-break modelling information between participants, with a special emphasis on the links between Universities, Research Organisations and Industry.
- To promote the comparison of numerical dam-break models and modelling procedures with analytical, experimental and field data.
- To promote the comparison and validation of software packages developed or used by the participants.
- To define and promote co-operative research.

These aims were pursued through a number of objectives:

- To establish needs of industry, considering a means of identifying dam owners, operators, inspectors etc. throughout Europe.
- To link research with industry needs - encourage participation; distribute newsletters to dam owners and other interested parties.

- To create a database of test cases (analytical, experimental, real life) available for reference.
- To establish the state-of-the-art guidelines and current best practices for dam-break modelling within the technical scope of the Concerted Action. This leads towards establishing recommended European standard methods, procedures and practices for dam-break assessments.
- To determine future RTD requirements.

CONCERTED ACTION PROGRAMME

The project involved participants from over 10 different countries across Europe. All member states were encouraged to participate, with attendance at the programme workshops open to all and to expert meetings by invitation. Also, links with other experts around the world were welcomed to ensure that state-of-the-art techniques and practices were considered. The programme of meetings planned for the presentation, discussion and dissemination of results and information were as follows:

Meeting 1 Wallingford, UK. 2/3rd March 98(Expert Meeting)
A review of test cases and modelling work undertaken by the group up to the start of CADAM, followed by a review of test cases considered during the previous 6 months. Typical test cases included flood wave propagation around bends, over obstructions and spreading on a flat surface (physical modelling undertaken in laboratory flumes).

Meeting 2 Munich, Germany 8/9th October 98(Open Workshop)
Presentations and discussion on the current state of the art in breach formation modelling and sediment transport during dam-break events.

Meeting 3 Milan, Italy May6/7th 99(Expert Meeting)
Comparison and analysis of numerical model performance against a physical model of a real valley (Toce River, Italy) plus an update on breach modelling research.

Meeting 4 Zaragoza, Spain Nov 18/19th 99(Symposium)
Comparison and analysis of numerical model performance against a real failure test case (Malpasset failure) plus a presentation of the results and conclusions drawn from the work of the *Concerted Action* over the two-year study period.

MODELLING COMPARISONS

The programme of tests progressed from simple conditions to test the basic numerical stability of modelling codes, through to a real dambreak test case – the Malpasset failure. The aim of the programme was to progressively increase the complexity of the modelling, and in doing so to try and identify which models performed best under which conditions. Both breach models and flood routing models were considered during the project.

Flood Routing Analysis

Numerical Models The models applied in CADAM ranged from commercially available software to codes developed 'in-house' by the various participants. Participants ranged from 'End User' organisations such as ENEL (Italy), EDF (France) and Vattenfall (Sweden) to consultancy companies and universities undertaking research in this field. Many of the European participants codes were 2D codes based on depth averaged Saint Venant shallow water equations, but applying different numerical schemes utilising different orders of accuracy and source term implementations. Codes more familiar to the UK market included DAMBRK and ISIS (1D model - implicit finite difference Preissmann Scheme).

Analytical Tests Initial test cases were relatively simple, with analytical solutions against which the numerical modelling results could be compared. These tests included:

- Flume with vertical sides, varying bed level and width. No flow – water at rest.
- Flume with (submerged) rectangular shaped bump. Steady flow conditions.
- Dam-break flow along horizontal, rectangular flume with a dry bed. No friction used.
- Dam-break flow along horizontal, rectangular flume with a wet bed. No friction used.
- Dam-break flow along horizontal, rectangular flume with a dry bed. Friction used.

These tests were designed to create and expose numerical 'difficulties' including shock waves, dry fronts, source terms, numerical diffusion and sonic points. Results were presented and discussed at the 2nd IAHR Working Group meeting held in Lisbon, Nov. 96 (EDF, 1997).

Flume Tests Following the analytical tests, a series of more complex tests were devised for which physical models provided data (Fig 1). The aim was to check the ability of the numerical codes to handle firstly, specific 2D features, and then important source terms. These tests were:

- Dam-break wave along a rectangular flume with 90° bend to the left.
- Dam-break wave along a rectangular flume with a symmetrical channel constriction.
- Dam-break wave along a rectangular flume expanding onto a wider channel (asymmetrical).
- Dam-break wave along a rectangular flume with 45° bend to the left.

- Dam-break wave along a rectangular flume with a triangular (weir type) obstruction to flow.

The first three test cases were presented and discussed at the 3rd IAHR working Group meeting in Brussels (UCL, June 97) and the remaining two at the 1st CADAM meeting in Wallingford (CADAM, March 98).

Photos courtesy of Sandra Soares, Université Catholique de Louvain, Belgium

Fig. 1 Shock waves generated from ‘dambreak’ flow around a 45° bend.

‘<u>Real Valley’ Physical Model</u> A model of the Toce River in Italy was used for the analysis of model performance against ‘real valley’ conditions (Fig 2). The advantage of comparing the numerical models against a physical model, at this stage in the project, was that the model data would not include any effects from sediment or debris that might mask features of numerical model performance.

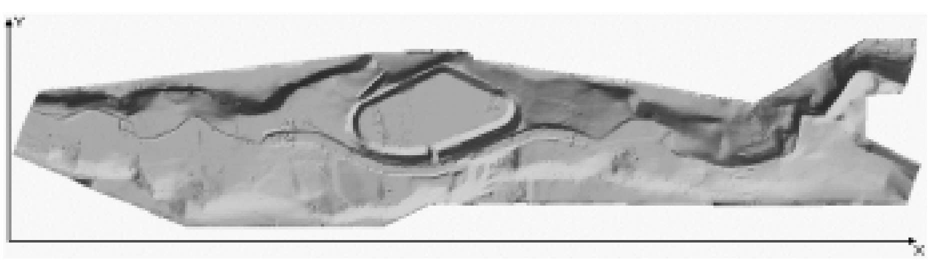

Fig. 2 Digital plan model showing the Toce River model

The model was provided by ENEL and, at a scale of 1:100, represented a 5km stretch of the Toce River, downstream of a large reservoir. An automated valve controlled flow in the model such that a flood hydrograph simulating partial or total dam failure could be simulated. Features within the downstream valley included a storage reservoir, barrage, bridges and villages (Fig 3).

Photos courtesy of Prof JM Hiver, Université Libre de Bruxelles, Belgium

Fig. 3 Bridge structure on the Toce model and a dambreak flow simulation

Real Failure Test Case – The Malpasset Failure The Malpasset Dam failure was selected as the real case study for the project since:

- The data was readily available through EDF (France)
- It offered a different data set to the commonly used Teton failure
- In addition to field observations for peak flood levels there were also timings for the failure of three power supply centres
- Data from a physical model study undertaken by EDF in 1964 (Scale 1:400) was also available

Modelling focused on the first 15km of valley downstream of the dam for which there was field data to compare against model predictions. This stretch of valley included features such as steep sided valleys, side valleys / tributaries and bridge / road crossings.

Breach Analysis

One of the four CADAM meetings was devoted to breach formation and sediment and debris effects. A comparison of the performance of breach models was undertaken using two test cases. The first test case was based on physical modelling work performed at the Federal Armed Forces University in Munich. The simulation tested was for a homogeneous embankment represented by a physical model approximately 30cm high. The second test case was based on data from the Finnish Environment Institute, derived from past collaborative research work undertaken with the Chinese. This work analysed the failure of an embankment dam some 5.6m high (Loukola et al, 1993).

SELECTED RESEARCH FINDINGS

The following sections highlight some selected issues identified during the CADAM project:

<u>Flood Routing</u>

It was not possible to uniquely define a single best model or single best approach for dambreak modelling within the scope of the study since the various models and approaches performed differently under varying test conditions. Equally, a more in-depth analysis of the significant quantities of test data collected is now required to understand some of the performance features identified. It was possible, however, to identify some recurring features and issues that should be considered when defining best practice for dambreak modelling. These include (in no particular order):

<u>Wave Arrival time</u> The speed of propagation of the flood wave is an important component of dambreak modelling since it allows emergency planners to identify when inundation of a particular area may be expected. It was found that 1D and 2D models failed to reproduce this accurately and that 1D models consistently under predicted the time (i.e. flood wave propagated too quickly) and 2D models consistently over predicted this time (i.e. flood wave propagated too slowly).

Figure 4 shows wave travel times for one set of test data. The 1D models (left) show a scatter of results, probably due to the range of numerical methods applied. Results shown spread across the observed data. Later tests showed a tendency to under predict the wave speed. Many of the 2D models used similar numerical methods perhaps resulting in the tight clustering of data, however the results here (and repeated later) show a consistent over prediction of wave speed (right).

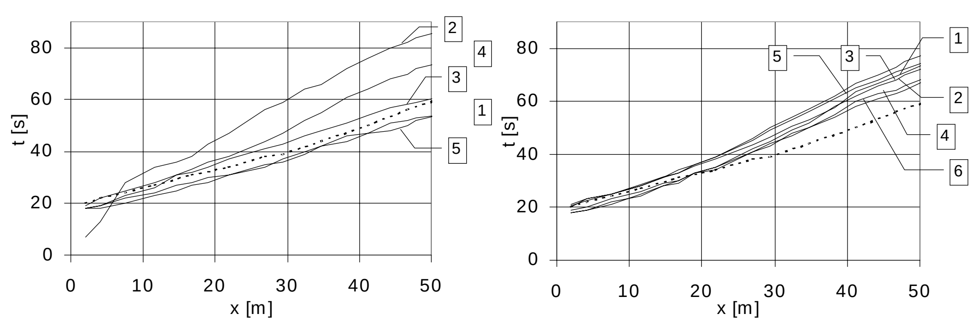

Fig. 4 Summary of flood wave travel times for 1D models (left) and 2D models (right)

Flood wave speed is poorly modelled – 1D models over predict wave speed, 2D models under predict wave speed.

Use of 1D or 2D Models It was found that the 1D models performed well in comparison with the 2D models for many of the test cases considered. It is clear, however, that there are instances where a 2D model predicts conditions more effectively than a 1D model. In these situations a 2D model should be used or the 1D model should be constructed to allow for 2D effects. These situations are where flow is predominantly 2 dimensional and include flow spreading across large flat areas (coastal plains, valley confluences etc), dead storage areas within valleys and highly meandering valleys. Simulation of these features using a 1D model will require experienced identification of flow features, reduction of flow cross section and addition of headloss along the channel.

A promising development that may offer a significant increase in model accuracy from a 1D model but without the heavy data processing requirements of a 2D model, is the use of a 'patched' model. This is where areas of 2D flow may be modelled using a 2D approach 'patched' within a 1D model (Fig 5). This technique requires further development and validation, but seems to offer significant potential.

In relation to the additional effort required for 2D modelling, 1D models perform well but cannot be relied upon to simulate truly 2D flow conditions. An experienced modeller is required to apply a 1D model correctly to simulate some 2D flow conditions.

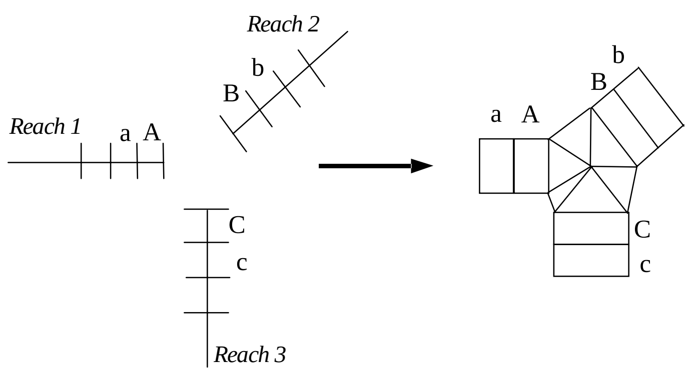

Fig. 5 2D patches within a 1D model to improve model accuracy whilst limiting processing requirements

Modeller Assumptions It was clear just from the test cases undertaken (and also supported by an independent study undertaken by the USBR (Graham, 1998)) that the assumptions made by modellers in setting up their models, can significantly affect the results produced. Graham (1998) deliberately gave identical topographic and structure data to two dambreak modellers and asked them to undertake independent dambreak studies for the same site. The results varied significantly, and particularly in terms of flood wave arrival times. Variations in breach formation, valley roughness and simulation of structures contributed to the differences.

Modelling assumptions can significantly affect the model results. Different modellers may produce different results for an identical study. Care should be taken to ensure only experienced modellers are used and that all aspects and assumptions made are considered.

Debris and Sediment Effects It is unusual to find debris and sediment effects considered in detail for dambreak studies but it is clear from case studies and ongoing research that the movement of sediment and debris under dambreak conditions can be extreme and will significantly affect topography, which in turn affects potential flood levels. Case studies in the US have shown bed level variations in the order of 5 to 10m.

Debris and sediment effects can have a significant impact on flood water levels and should be considered during a dambreak study. These effects offer a significant source of error in flood prediction.

Mesh Convergence The definition of a model grid in 2D models, or the spacing of cross sections in 1D models, can significantly affect the predicted results. Models should be checked as a matter of routine to ensure that the grid spacing is appropriate for the conditions modelled and that further refinement does not significantly change the modelling results.

Mesh or section spacing should be routinely checked when modelling

Breach Modelling

Existing models are very limited in their ability to reliably predict discharge and the time of formation of breaches. Figure 6 below shows a typical scatter of modelling results found for the CADAM test cases. Models comprised a range of university and commercial codes, including the NWS BREACH code.

It is also clear that there is little guidance available on failure mechanisms of structures, which adds to the uncertainty of conditions assumed by modellers.

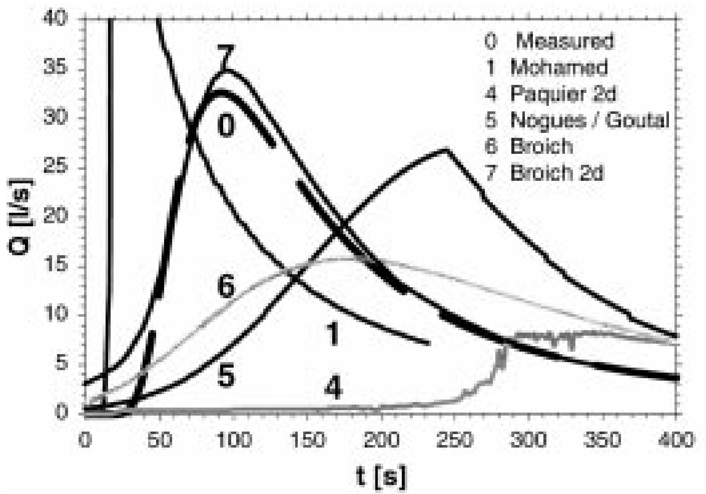

Fig. 6 Typical scatter of model results trying to predict breach formation

There are no existing breach models that can reliably predict breach formation through embankments. Discharge prediction may be within an order of magnitude, whilst the time of breach formation is even worse. Prediction of breach formation time due to a piping failure is not yet possible.

The NWS BREACH model is only calibrated against a very limited data set. The author (Danny Fread) confirmed that it is based on approximately 5 data sets.

Existing breach models should be used with caution and as an indicative tool only. A range of parameters and conditions should be modelled to assess model performance and results generated.

There is a clear need to develop more reliable predictive tools that are based on a combination of soil mechanics and hydraulic theory.

End User Needs

Throughout CADAM, the project focused on the practical needs of end users. Attempts were made to quantify a number of issues, both by end users and academic researchers alike. The initial response to the question of what accuracy models could offer and what was required from end users was limited. Without agreement on such issues it is impossible to determine whether existing modelling tools are sufficient or not! This perhaps reflects the current uncertainty of end users with regards to legislation and appropriate safety measures and of modeller's appreciation of processes and data accuracy. It was suggested that the level of modelling accuracy should be appropriate for the site in question (i.e. more detailed for urban areas). Water level prediction should be appropriate to the mapping required, and the mapping should be at a scale sufficient for emergency planning use (i.e. to identify flood levels in relation to individual properties). This suggests an inundation mapping scale of approximately 1:5000 for developed areas.

Inundation maps should be undertaken at a scale appropriate for use in emergency planning. For urban areas it is suggested that this should be at a scale of 1:5000 or greater. Modelling accuracy should be consistent with the detail of mapping required (i.e. for the end user of the data)

Some Additional Points on DAMBRK_UK and BREACH

During the project, work undertaken by HR Wallingford identified a number of potential problems with the DAMBRK_UK and BREACH software packages.

Under certain conditions, it was found that the DAMBRK_UK package created artificial flow volume during the running of a simulation. For the limited conditions investigated this volume error was found to be as high as +13% (Mohamed (1998)). This error tended to be on the positive side, meaning that the flood levels predicted would be pessimistic. It may be assumed that similar errors exist in the original DAMBRK code. It was noted that model performance varied between DAMBRK, FLDWAV (released to replace DAMBRK) and BOSS DAMBRK. A detailed investigation into the magnitude and implications of these errors has not yet been undertaken.

Similarly, problems were also found with the BREACH software package. Under some conditions, predicted flood hydrographs were found to vary significantly with only minor modifications to input parameters. This erratic behaviour was discovered when considering the differences between piping and overtopping failure, by tending the piping location towards the crest of the dam. Erratic performance was also confirmed by a number of other CADAM members.

Figure 7 shows a plot of flood hydrographs generated by BREACH for an overtopping failure and a piping failure located just 3cm below the crest. Logic dictates that these hydrographs should be very similar however the results show a significant difference in both the volume of the hydrograph as well as the timing.

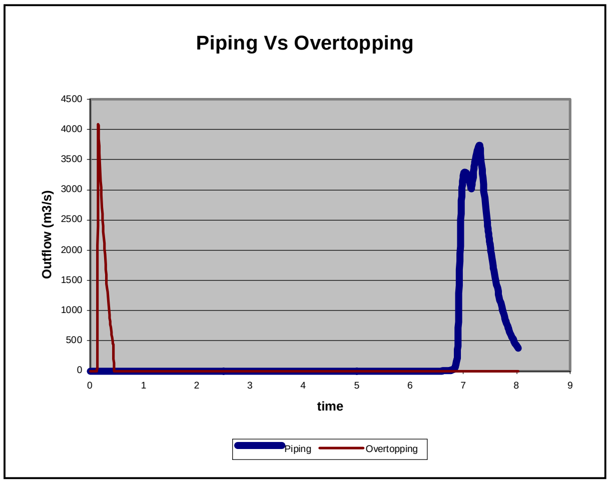

Fig. 7 Different outflow hydrographs produced by breach for an overtopping failure and a piping failure located 3cm below the crest.

CADAM CONCLUSIONS

The CADAM project has reviewed dambreak modelling codes and practice and identified a range of issues relating to model performance and accuracy. A number of these issues have been outlined above. When considering all aspects contributing to a dambreak study it was found that breach formation prediction, debris and sediment effects and modeller assumptions contribute greatly to potential prediction errors.

Full details of all findings and conclusions may be found in the project report which has been published by both the EC and the IAHR, and which may also be found on the project website at:

www.hrwallingford.co.uk/projects/CADAM

BEYOND CADAM

Following completion of the CADAM project, it was a logical extension of the work to review the recommendations and develop a programme of research work aimed at addressing the key issues. Working within the European Commission 5th Framework Research Programme, a major research proposal was developed by a new consortium of organisations, some of whom had worked on the CADAM project and others whom joined the team to provide additional and more varied expertise. This proposal was named SECURE (Safety Evaluation of Man Made Water Control Structures in Europe)

Funding of European research is undertaken on a competitive basis with a finite volume of money with which to fund projects. The original proposal initially failed to receive funding and required considerable reworking twice before funding was (informally) agreed. During this process the extent of the proposed research was significantly reduced. However, the final proposal, named IMPACT (Investigation of Extreme Flood Processes & Uncertainty), is now subject to contract negotiation with the European Commission and research work should commence towards the end of 2001.

The following sections are drawn from the European Commission discussion documents and provide an overview of the proposed work. Whilst the work programme is not yet final, it is unlikely to change significantly from the work described here.

THE IMPACT PROJECT - OVERALL AIM

The problem to be solved in the IMPACT project is to provide means of assessing and reducing the risks from the catastrophic failure of dam and flood defence structures.

THE EUROPEAN NEED FOR IMPACT

In the EU, the asset value of dam and flood defence structures amounts to many billions of EURO. These structures include, for example, dams, weirs, sluices, flood embankments, dikes, tailings dams etc. Several incidents and accidents have occurred which have caused loss of human life, environmental and economic damages. For example, in May 1999 a dam failed in Southern Germany causing four deaths and over 1 Billion EURO of damage. In Spain in 1982, Tous dam failed when still under construction with the result of 8 casualties, 100,000 evacuated people and economic losses worth 1500 MEuro. In 1997, also in Spain, a dam failed on the Guadiamar river, not far from Sevilla, causing immense ecological damage from polluted sediments released into the river valley during the failure. The dam failure at Malpasset (French riviera) in 1959 caused more than 400 casualties.

The risk posed by a structure in any area is a combination of the hazard created by the structure (e.g. flooding) and the vulnerability of the potential impact area to that hazard (e.g. loss of life, economic loss, environmental damage). To manage and minimise this risk effectively it is necessary to be able to identify the hazards and vulnerability in a consistent and reliable manner. Good knowledge of the potential behaviour of the structure is important for its proper operation and maintenance in emergency situations such as high floods. In addition, prior knowledge of the potential consequences of failure of a dam or flood defence structure is essential for effective contingency planning to ensure public safety in such an emergency.

In many areas related to structure failure our current understanding and ability to predict conditions is limited, so making the management of risk difficult. This project aims to advance the risk management process by improving knowledge of, and predictive tools for, the underlying processes that occur during and after failure. By both improving knowledge of the underlying processes and quantifying probability / uncertainty associated with these processes, the effect of these processes within the risk management system may be demonstrated and subsequently built into consideration the risk management process to improve reliability and safety. Many of the 'underlying processes' proposed for research were highlighted during the recent CADAM European Project as areas requiring further research.

A common problem integral to the failure process is that of sediment and debris movement. The sudden release of water from a control structure brings with it intensive scour in the flow downstream. Close to the structure, the flow is extremely destructive; it can scour aggressively material from the riverbed and floor of the valley, changing completely the shape of the valley, or even diverting the river from its natural course. The flow will uproot vegetation and trees, demolish buildings and bridges and wash away animals, cars, caravans etc. The floating debris can be transported for substantial distances whilst the heavier material is deposited or trapped once the flow velocity attenuates. At a different level, it is the erosion of material from an embankment or dam that occurs during breaching and hence dictates the rate at which flood water may be released, and the location at which this may occur.

The IMPACT project is of relevance to broad communities of user organisations, some of which are Partners in the IMPACT project team. The IMPACT project is organised in several complementary and interdependent themes to deliver the objectives of the research.

IMPACT: SCIENTIFIC AND TECHNICAL OBJECTIVES

The objectives of the IMPACT project are represented schematically in Figure 8 below. Specific objectives are therefore to:

1. Advance scientific knowledge and understanding, and develop predictive modelling tools in three key areas associated with the assessment of the risks posed by dam and flood defence structures:
    a. the movement of sediment (and hence potential pollutants) generated by a failure

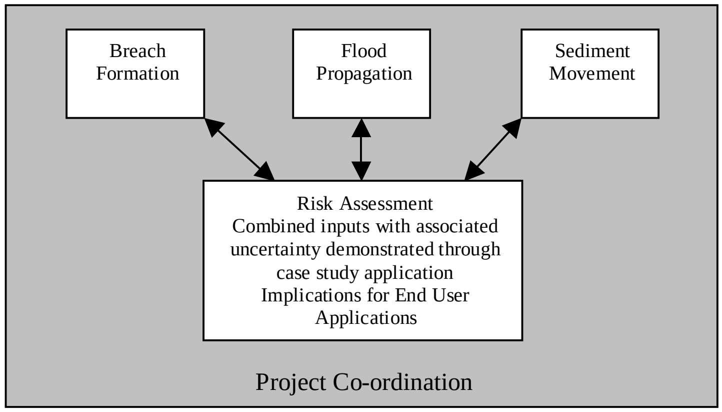

Fig. 8 Structure of the IMPACT work programme

b. the mechanisms for the breaching of embankments (dams or flood control dykes) and factors determining breach location
c. the simulation of catastrophic inundation of valleys and urban areas following the failure of a structure

2. Advance the understanding of risk and uncertainty associated with the above factors and combine these factors through a single system to demonstrate the risk / uncertainty associated with application of the end data (i.e. asset management, emergency planning etc.)

These objectives will be undertaken with careful reference to past and ongoing research projects related to these topics, including the CADAM and RESCDAM projects.

An important subsidiary objective of the IMPACT Partners is to ensure end-user relevance, acceptance and implementation of the outputs of the research. To this end, the IMPACT project Partners will develop the methodologies using demonstration sites and applications wherever appropriate. The project will include:

- breaching of large scale test embankments (6m high embankments) to investigate breach formation mechanisms and the relationship between prototype and laboratory simulation
- field assessment of sediment movement following large scale embankment failure
- simulation of catastrophic flooding through the streets of a European city
- a combined assessment of extreme flood conditions and prediction uncertainty for a real or virtual site comprising dam / flood defence and urban area.

IMPACT: BENEFITS OF THE RESEARCH PROJECT

The successful completion of the IMPACT project is expected to lead to:

- improved scientific knowledge and understanding of extreme and aggressive flood flows following the catastrophic failure of a water control structure
- Specific scientific knowledge and understanding relating to breach formation through dams and flood defence structures, movement of sediment under extreme flood conditions and the simulation of flooding in urban areas
- improved understanding of the risk associated with the potential failure of dams and flood defence structures ultimately leading to reduced risks of failure and hence a reduction in long-term costs
- improved understanding of the uncertainty associated with the prediction of extreme flood conditions and processes
- improved public safety through emergency planning and community disaster preparedness in the event of a failure
- enhanced prospects for EU-based consultancies in the International Water and Hydropower markets

IMPACT: OVERVIEW OF WORK PROGRAMME

As shown in Figure 8, the IMPACT project has been structured according to 5 *Theme Areas*. These *Theme Areas* are:

Theme 1	Project Integration, Co-ordination and Delivery
Theme 2	Breach Formation
Theme 3	Flood Propagation
Theme 4	Sediment Movement
Theme 5	Combined Risk Assessment & Uncertainty

The objectives and proposed work for each of these Theme Areas is presented in more detail below:

<u>Theme 1</u> <u>Project Integration, Co-ordination and Delivery</u>

The IMPACT project involves 9 organisations drawn from 8 European countries and thus will require careful attention to the management of the research to ensure that it delivers it outputs. The project integration, co-ordination and delivery is a core management function of the project Co-ordinator. The project integration will be achieved through facilitation of communication between each of the project themes and the researchers engaged in the work packages. There will be a regular meeting of the Theme leaders approximately every four to six months. Where possible, these meetings will be scheduled with other project meetings to minimise the travel costs. Full team meetings will be held at project workshops, of which four are scheduled during the 36-month period. These workshops will provide opportunities for representatives of all the research teams to discuss their findings and future approaches. The Co-ordinator (M Morris: HR Wallingford) will use the project workshops to review progress and define the detailed work programme for the coming months.

The Co-ordinator will establish a project Internet site with public and private areas. The public area will give information on the definitive project outputs, whilst the private site with an FTP area will be the main vehicle for electronic communication of data, software and results between the IMPACT project team members. An Internet based email database will be established to allow any interested parties to register their email address for receipt of project newsletters, meeting details etc. The Co-ordinator will take final responsibility for the documentation and reporting of the project. Project team members will be encouraged to publish the results of the research in refereed scientific journals and conferences as appropriate. Public outputs from the project will be recorded and made available through the public area of the project Internet site.

<u>Theme 2</u>   <u>Breach Formation</u>

The problem to be solved in this theme is the lack of quantitative understanding of the modes and mechanisms involved in the failure of dams and flood defence structures. Without such understanding, the rate of outflow from a failed structure cannot be assessed and hence the risks posed by the structure cannot be assessed with confidence. The approach to the research proposed in the IMPACT project is a combination of experimental and theoretical investigations, leading to a new modelling procedure for the failure of embankments. Three components of failure modes will be investigated, internal erosion, overtopping and slope stability during the breach enlargement. The methods will be validated as far as possible against data from the physical experiments as well as actual failures. The large-scale experimental facilities available to the IMPACT partners will allow the factors that govern the initiation and growth of breaches to be studied under controlled conditions. However, the issue of scaling from the laboratory to the prototype scale must be addressed. A novel part of the experimental programme is the rare opportunity to include field tests at large scale. A test site has been identified in Norway located between existing dams where a 6m high embankment may be constructed and then tested to failure using controlled flow released from the upper dam. Five failure tests are planned. The location and test programme means that no damage to infrastructure will occur, also with minimal environmental effect. Individual work packages within this *Theme Area* include:

- Breach formation processes – controlled failure of 6m high embankments to identify key processes
- Breach formation processes – laboratory physical modelling of embankment failure to identify key processes

- Model development and comparison - development and comparison of breach model performance through use of a common modelling framework
- Breach location – development of a methodology / prototype tool for a risk based approach to identifying breach location

Theme 3 Flood Propagation

The problem to be solved in this theme is to produce reliable modelling methods for the propagation of catastrophic floods generated by the failure of a water-control structure (often called the *dam-break* problem). The intensity of the flood will depend upon the initial difference in depth between the impounded level behind the control structure and the land level on the other side. Hence the research in this theme will concentrate upon the dam-break flood problem but the techniques will also be applicable to the failure of flood embankments. The overall objectives for this theme are:

- To identify dam-break flow behaviour in complex valleys, around infrastructure and in urban areas, and the destructive potential of these catastrophic flood waves.
- To compare different modelling techniques & identify best approach, including assessment of accuracy (in relation to practical use of software).
- To adapt existing and develop new modelling techniques for the specific features of floods induced by failure of man made structures.
- To develop guidelines for an appropriate strategy as regards modelling techniques, for a reliable and accurate prediction of flooded areas.

The approach to be adopted is to:

- compare different mathematical modelling techniques
- identify the best approaches, including assessment of implementation of the methods in industrial software packages
- check the accuracy and appropriateness of the recommended methods by validation of the models against the results from physical experimentation.
- validate the different modelling techniques adopted, both existing and newly developed against field data obtained from actual catastrophic flood events.

The research has been organised into two work-packages each subdivided into several distinct tasks; for each task there is a Technical Co-ordinator and a team of Partners involved in the activities. The two work-packages are:

- Urban flood propagation
- Flood propagation in natural topographies

Theme 4 Sediment Movement

The problem to be solved in this theme is to improve the predictions of the motion of sediments in association with catastrophic floods. The nature of the problem is different form that in normal flood flows in that the quantity and size of sediment will be much greater in the catastrophic flood flow. This is an important issue for an accurate prediction of the downstream consequences:

- the river bottom elevation can vary by tens of meters
- or the river can be diverted from its natural bed (as for the Saguenay river tributary – the Lake Ha!Ha! damn failure, Canada, in 1997),

with the associated impact on the flooded areas. The approach adopted in the IMPACT project is to combine physical experiments designed to improve our physical understanding of these cases with the development and testing of mathematical modelling methods for simulation of these flows. The IMPACT Partners will use the extensive experimental facilities available to them in undertaking the experimental programme. An output of the research will be a set of well-documented experimental investigations of flows with transported sediment, which could serve the international research community as benchmarks for future theoretical developments outside the scope of the current IMPACT project.

The research is divided into two work-packages that address:

- near field sediment flow in dam-break conditions
- geomorphological changes in a valley induced by dam-break flows (far field)

Theme 5 Combined Risk Assessment and Uncertainty

Themes 2-4 outline proposed research into processes that are currently poorly understood or poorly simulated by predictive models. An important aspect of any process that contributes towards an overall risk assessment (i.e. prediction of flood risk) is an understanding of any uncertainty that may be associated with prediction of that particular process. For example, a flood level may be predicted to reach 20m and an emergency plan developed to cope with this. However, if the uncertainty associated with this prediction is ±2m, then different measures may be taken to manage this event. The problem to be solved in this theme, is to quantify the uncertainty associated with each process contributing to the risk assessment and to demonstrate the significance of this for the end application. This may be in the form of uncertainty associated with flood level prediction, flood location, flood timing or flood volume – depending upon the particular application of data.

Uncertainty will be quantified by working closely with the fundamental research being undertaken in Themes 2-4 and demonstrated through a number of case study applications. The procedure for combining the uncertainty associated with different data will depend upon the process itself. This may require multiple model simulations or combination through spreadsheet and / or GIS systems as appropriate.

Having identified process uncertainty and the effect that particular processes may have on the end application, it will also be possible to identify the importance (with respect to the accuracy of a risk assessment) that each process has and hence the effort that should be applied within the risk management process to achieve best value for money.

IMPACT CONCLUSIONS

Subject to final contract negotiations with the European Commission, the IMPACT project should commence towards the end of 2001 and run for a period of 3 years. The research findings from this project should enhance understanding of extreme flood processes and simulation including breach formation, flood routing and sediment movement. It is intended that research undertaken for the IMPACT project shall remain focussed upon the needs of end users, and active participation by representatives from industry worldwide shall be sought. Technical knowledge relating to the specific extreme event processes will be presented but also analysed in the context of end user applications with the aim of demonstrating not only what is known, but also the uncertainty related to that knowledge and how this might influence direct applications.

For more information on this project, and to sign up to the project email list, visit the project website (from November 2001) at:

www.hrwallingford.co.uk/projects/IMPACT

or contact the project Co-ordinator directly on:

m.morris@hrwallingford.co.uk

ACKNOWLEDGEMENTS

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Université Catholique de Louvain (Belgium), CEMAGREF (France), EDF/LNH (France), Université de Bordeaux (France), INSA Rouen (France), Federal Armed Forces University Munich (Germany), ENEL

(Italy), Politechnika Gdanska (Poland), Universidade Tecnica de Lisboa (Portugal), Universidad de Zaragoza (Spain), Universidad Santiago de Compostela (Spain), Vattenfall Utveckling AB (Sweden), University of Leeds (UK), HR Wallingford (UK).

Special thanks should also go to the following organisations that have undertaken, or made available data from, physical modelling work:

Université Catholique de Louvain (Belgium), Université Libre de Bruxelles (Belgium), LNEC (Portugal), ENEL (Italy), Federal Armed Forces University Munich (Germany), The Finnish Environment Institute.

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Issues, Resolutions, And Research Needs Related To Dam Failure Analysis
USDA/FEMA Workshop
Oklahoma City June 26 - 28, 2001

Embankment Breach Research in Norway

Senior Advisor Kjetil Arne Vaskinn, dr.ing.
Statkraft Grøner AS[1]

1. INTRODUCTION

The modern dam building in Norway started around the turn of the century, when we started to exploit our hydropower resources. Hydropower is today one of Norway's major natural resources. The development of the resource has resulted in construction of many reservoirs. 2500 dams are controlled by the Norwegian Water Resources and Energy Directorate (NVE). NVE is the dam-safety authority in Norway. The dams controlled by NVE are higher than 4 m or have a reservoir capacity exceed 0,5 Mill.(m^3).

In the beginning most of the dams was masonry or concrete dams. After 1950, large embankment dams began to dominate the scene.

A water reservoir behind a dam represents an enormous energy potential, which might cause catastrophic damage in case of a dam failure. The dams therefore pose a risk to the downstream area. To manage and minimize this risk effectively it is necessary to be able to identify the hazards and vulnerability in a consistent and reliable manner. Good knowledge of the behavior of the structure is important for the maintenance and proper operation. In addition, prior knowledge of the potential consequences of failure of a dam or flood defense structure is essential for effective contingency planning to ensure public safety.

The issue of dam safety has become more and more important in Norway during the last years and much money has been spent to increase the safety level. The dam owner is responsible for the safety of his dams. He has to follow the requirement and guidelines from NVE:

- [1] Statkraft Grøner is one of the major consulting firms in Norway with 300 employee in 1998 and an annual turnover 42 mill. US dollar. The company has a high expertise in the field of research and development, working closely with academic research groups and the hydropower industry. The company is fully owned by Statkraft SF, the largest Hydropower Company in Norway. Statkraft SF Operates 55 power plants and has ownership in 36 more. The average annual production for Statkraft in Norway is 36 TWh (30% of Norway's total). Statkraft SF owns 113 water reservoirs with a capacity of 33,7 billion m3 (40% of Norway's total storage capacity)

1. Contingency planning for abnormal situations
2. Safety revisions
3. Load recording
4. Damage and accident reporting
5. Risk analysis
6. Discussions of the failure probability and studies on impact of failure

To make sure that the dam-safety work is done in a proper way, NVE has made several guidelines. These include "*Guidelines for simulation of dam-break*"(Backe et al 1999). All the dam-break simulations in Norway are made according to these guidelines.

The system for revisions of dams, developed by NVE, has been operation for several years. The experience so far is good. From time to time the result from a safety revision implies that the dam-owners have to put in a lot of money to fulfill the requirements. In most cases this is done without any discussions. Sometimes, however, there is a discussion between the owner of a dam and NVE based on different understanding of the guidelines and a lack of common understanding of the basic mechanism in how the strength and stability of the dam can be improved. The focus for discussion is now the new guidelines for dam-safety, not yet put into operation.

The most frequent theme for discussion is whether or not a dam satisfies the requirement to:

- Stability when exposed to normal loads.
- Stability with extreme loads e.g. major leakage and resistance against erosion in case of overtopping.

Stability of rock filled dams is determined mostly as a function of the shear strength of the rock filling. Stability in case of extreme loads is also dependent of the shear strength, but in these cases there is a big uncertainty in the loads.

The regulations require that the dams can resist a certain leakage through the core. An ongoing project (Cost efficient rehabilitation of dams) also put the focus on the breaching mechanism in the case of a major leakage.

Dam break analysis is performed to assess the consequences of dambreak and is a motivating factor for the dam safety work. The routines used today to in Norway give a too simplified description of the development in the breach in our rock-filled dams. The materials and the way the dam is constructed are not taken into consideration. Due to this most of the work done on the dam to improve the security will have no visible influence on the development of the dambreak and on the downstream consequences of the break, when performing the dambreak simulation. This is not logical and gives not incentives to the dam safety work. The result of this can also be a wrong classification of a dam.

Based on these experiences Norway has started a new project with the main objective of improving the knowledge in this field.

Parallel to the planning of a Norwegian project there, European research institutions have been working for establishing a common within the filed of dam-safety. The project is called IMPACT and is presented in detail by Mark Morris. *The problem to be solved in the IMPACT project is to provide means of assessing and reducing the risks from the catastrophic failure of dam and flood defense structures* (quote from the application to EU for funding of IMPACT).

2. MAJOR OBJECTIVES

The scope of the project is to improve the knowledge of, and to develop predictive tools for the underlying processes that occur during and failure. By doing so the proper decisions can be taken for improving the dam safety taking into account the technology and economy.

The objectives of the project are:

- To improve the knowledge on the behavior of rock filled dams exposed to leakage.
- To get knowledge on the developent of a breach.

This knowledge will be used to:

- Develop simulation tools that will be used in the planning of dam safety work.
- Develop new criteria for design of dams
- Develop criteria for stability and failure mechanics of dams.

3. PROJECT PLAN.

The Norwegian project consists of 4 sub-projects:

1. Shear strengths and permeability of rock-fillings
2. Stability of the supporting fill and dam-toe in rockfill dams exposed to heavy leakage
3. Breach formation in embankment-dams (rock-filled dams)
4. Breach formation in concrete dams

A rockfill dam is defined as an embankment dam comprising more than 50% by volume of fill obtained from rock quarry or rock excavation. (Konov, 2001)

The IMPACT-project project consist of 4 themes:

1 Breach Formation
2 Flood Propagation
3 Sediment Movement
4 Combined Risk Assessment and Uncertainty

Sub-project 3 in the Norwegian project and theme 2 in IMPACT has the same objectives. Some of the problems that will be solved in sub-project 1 and 2, will give information that is relevant for IMPACT. Through coordination of these to major projects we hope to improve the knowledge about embankment dams

Mark Morris has presented the details of IMPACT. In the following chapters a short description of the Norwegian project will be given.

3.1 Shear strengths and permeability of rock-fillings

Through the process of reevaluation of rock-filled dams the question of the shear-strength has been asked. Very few dams have a documentation of the shear-strength of the rock-fillings based on test of the rock materials. In most cases the planning is based on experience from similar dam-constructions and geological conditions.

The main question to answer in the project will be what the correct or best parameters to describe the materials are. Physical test and experience will be used. Some tests have been done at some of the largest rockfill-dams in Norway. This knowledge will be used to correlate the shear-strength from single tests of the rock material to roughness, shape of the grains, pressure strength.

Permeability or hydraulic conductivity is important for the leakage through the supporting fill and for the erosion during a dam failure. Existing knowledge and data on this topic will be collected through a literature review. Test of the permeability in the large-scale test dam will be performed.

3.2 Stability of the supporting fill and dam-toe in rock-filled dams exposed to heavy leakage

Sub-project no 2 will focus on developing of tools or routines for assesment of the stability of a dam exposed to leakage through or over the core.

The objectives of the tests are:

1. To find the connection between the drainage capacity through a rock-filled dam, the size of the stones, layout of the filling/dam-toe etc. This information will be used setup of new guidelines for assessment of old dams and for layout and dimensioning of new dams in general and specifically the dam-toe.
2. To increase the knowledge of the permeability of rock-fillings in general.
3. To find and verify the connection between different scaling. (1:10, 1:5 and prototype)

A computer simulation program will be developed to analyze the flow through a rock filling. Criteria that tells when a rock-filled dam will collapse either due to erosion of the individual stones or a major break along shear flater through the supporting fill, will be developed.

The simulating program will be tested on physical models in large scale

3.3 Breach formation in rock-filled dams

The objective of this sub-project is to improve the understanding of the breach formation process that occurs in and through embankments, with a special focus on rockfill dams.

Breach formation covers factors that will lead to an uncontrolled release of water from the structure. The most common modes of failure for an embankment are from water overtopping the crest or internal erosion also called piping. The ability to predict the location and rate of development of a breach through a flood embankment or dam is limited.

The most commonly applied approach is the deterministic BREACH model developed in the late 1970's at the US National Weather Service (USNWS). Several parametric relationships based upon analysis of actual failures of dams are also in use. In Norway the relationship developed by Froelich (Backe D et al.1999) is used.

Most of the tests and analysis have been of homogeneous structures of non-cohesive material. The failure of multi-element structures incorporating an impervious core remains poorly understood.

Experimental tests will be undertaken to support the theoretical development of models of the failure modes and rates of failure. These tests will be made as part of the IMPACT project. Investigation will be made of the factors contributing to breach location and analysis of the likely probability of failure resulting from these factors.

The tests will be completed through "large scale" tests. Based on the results from these tests a simulation program will be developed for simulation of the breach formation in these kinds of dams.

3.4 Breach formation in concrete dams

This subproject will focus on the breach formation in concrete dams. Finite element methods will be used. The project will take advantage of the experience of concrete technology for simulation of failure of concrete dams.

There exist several very advanced simulation programs that can be used e.g. ABAQUS. This program was developed to help engineers to design the off-shore platforms that are used for oil-drilling in the North See.

4. PHYSICAL/SCALE MODELING

There will be several test of physical modes in the in the laboratory and in the field (large-scale test). This test are necessary in order to find the answers in sub-project 1, 2 and 3 and also for the questions asked in theme 2 of IMPACT.

4.1 Tests in the laboratory.

There will be laboratory test both in Norway and in UK (Wallingford). The tests in UK will be undertaken to examine the different aspects of breach formation. This part of the laboratory modeling will use embankments approximately 0.75m in height and the experiments will investigate:

- overtopping failures for water flowing over the crest of an embankment
- piping failures where fine material is progressively eroded through the body of the embankment

Initial tests will cover homogeneous non-cohesive material – an idealized embankment. Tests will then progressively tend towards real embankment designs through the analysis of cohesive material and composite structures. Tests will measure flow-rate, the hydraulic heads, and evolution of the crest erosion and piping to establish the erosion rates of the material.

The main issues of the Norwegian laboratory tests are to find out any possible problem with the field tests. Several tests of the dam-toe will be made. Focus will be on the following:

1. Scaling effects
2. Size of the materials (stones)
3. Grain size distribution of material
4. The shape (layout) of the dam-toe
5. The importance of the downstream-water level.

In the laboratory we will use to test-flumes: one in the scale 1:5, the second one in scale 1:10. According to the plans there will be 13 different tests of the dam-toe. These are shown in table 1.

Table 1. Tests in the laboratory

Test no		**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**
Scale	1:10	*		*	*	*	*						*	*
	1:5		*					*	*	*?	*?	*?		
Size of the stones	D_{50} [mm]	500	500	100	300	100 0	200 0	100	100 0	500	500	500	500	500
	Sizing	E	E	E	E	E	E	E	E	V	E	V	E	E
Shape	Slope	1,5	1,5	1,5	1,5	1,5	1,5	1,5	1,5	1,5	3,0	3,0	1,5	3,0
	Water level	L	L	L	L	L	L	L	L	L	L	L	H	H
Reproducibilityt														
Scale		*1	*1	*2		*3		*2	*3					
Size of the stones		*1	*2	*1	*1	*1	*1	*2	*2					
Sizing			*1							*1	*2	*2		
Slope			*1							*2	*1	*2		
H/L waterlevel			*1								*2		*1	*2

E: Uniform, V: well graded, L: low water level downstream, H: high water level downstream
*: referring to which tests can be compared. E.g.: If we want to study the scaling effects, results from test 1 and 2, 2 and 7, and 5 and 8 should be compared.

Key figures for the flumes are shown in table 2.

	Scale 1:10	**Scale 1:5**
Width (meter)	2,20	4,0
Length (meter)	10,0	10,0
Depth (meter)	0,75	1,43
Maximum discharge (l/s)	320	600

We will also make some test with the focus of planning of the field test.

All of the tests in table 1 are used to evaluate the stability of the stones in the outflow area.

Test no 1,2,3,5,7, and 8 will be used to assess if there are some scaling effects. Tests #1 to #8 are designed to help in evaluating the effect of the different sizes of the stones in the outflow area.

The results here will also be used to compare with data from earlier tests and projects:

- "Safety analysis of rock-filed dams", Dam safety project 1992.
- " Safe remedies for leaking embankment dams", ICOLD, Rio de Janeiro, 1982.
- "Flow through and stability problems in rockfill dams exposed to exceptional loads", Vienna 1991.
- " The risk for internal erosion in rock-filled dams and the calculation of turbulent coefficient of permeability", Norwegian research Council, 1991.
- "Extreme situations", Short course in dam safety, 1992.

The test #2, 9, 10 and #11 are identical except from the differences in the grain size distribution of the building material. Two of them are well graded. The other two have a uniform grain size distribution. These tests will be used to assess the difference in stability with the same characteristic size of the stones, but different grain size distribution.

Table 3 mixing of material

Table 3.Size of material in prototype

Test no.	**Size of stones (mm)**				**mixing**	
	d_{max}	**d_{60}**	**d_{50}**	**d_{10}**	**E/V**	**C_u**
1	750	600	500	240	E	2,5
2	750	600	500	240	E	2,5
3	150	120	100	48	E	2,5
4	400	360	300	144	E	2,5
5	1500	1200	1000	480	E	2,5
6	***1800***	***1600***	***1500***	***640***	E	2,5
7	150	120	100	48	E	2,5
8	1500	1200	1000	480	E	2,5
9	750	600	500	120	V	5
10	750	600	500	240	E	2,5
11	750	600	500	120	V	5
12	750	600	500	240	E	2,5
13	750	600	500	240	E	2,5

Tests #2 , #9, # 10 and #11is identical except for the slope of the downstream side: two of them have the slope of 1:3, the two other have a slope equal to 1:1,5. Results from these tests will be used to assess the stability of the toe, due to different slopes.

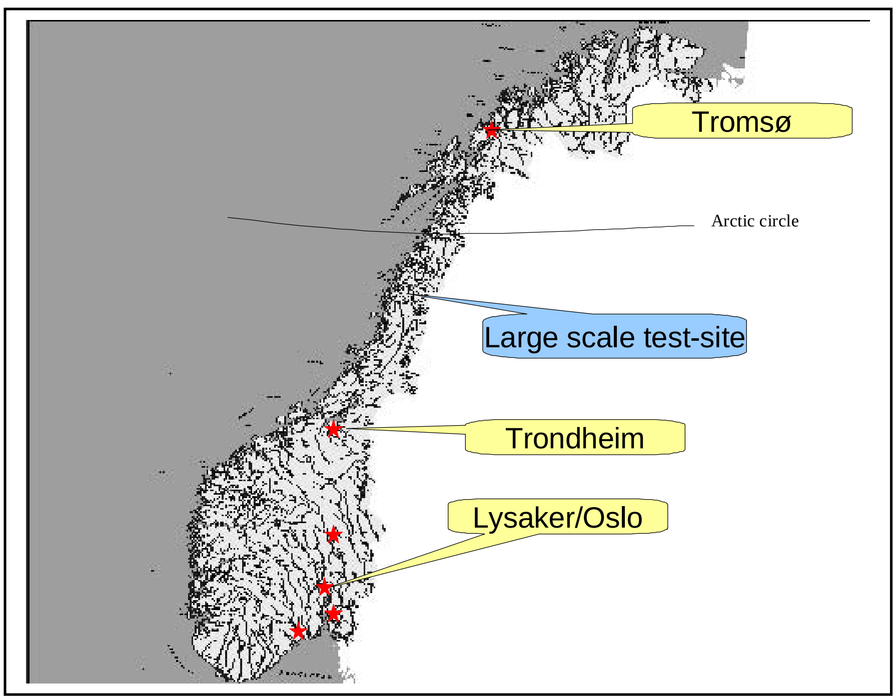
Test #2 and #12 are identical, the same is #10 and #13 except for difference in the water-level downstream of the dam. These tests will be used to compare the effect on the stability due to different level down stream of the dam.

The following data will be recorded in the tests:

- The pressure line in the filling
- Water-level upstream and downstream of the dam
- The discharge through the dam (measurd downstream of the dam)
- The water-level at the downstream edge of the dam_toe
- The grain size distribution curve.
- The porosity in a test volume
- Picture from the test
- Video recording of the test.

4.2 The field tests

The field test will be made downstream of one of the largest reservoir in Norway (The lake Røssvatnet). Statkraft SF is the owner of this reservoir and is an active partner in the project. The test site is in northern Norway, close to the Arctic Circle. Figure 1



The dam on this reservoir has just been revised. As a result of the safety revision Statkraft SF has made safety improvements on the dam. An overview of the area downstream of the dam is shown in figure 2. Figure 3 shows cross-section of the test-site and also a longitudinal section along the river. So far the focus in the project has been on the laboratory tests. The results from these test will give information and knowledge that will be used for the detailed planning

We are going to run two different kind of tests:

- tests of the stability of the dam-toe

- breach tests

A local contracting firm will be responsible for the building of the dam according to our specifications.

The release of water from the upstream-reservoir has to be done in close cooperation with the dam-owner, Statkraft SF.

The gates at Røssvassdammen have a total capacity up to 500m^3/s. The gates are new and the operation of them is easy and flexible. The high capacity through the gates gives us the opportunity to simulate breaching in a large reservoir (slow reduction in the water level in the reservoir as a function of time) and a small reservoir.

Prior to the tests we will establish a measurement station for discharge. The capacity of the gate as a function of the opening is known. By releasing a known discharge through the gates and record the corresponding water level a stage-discharge relationship will be established.

Exact measurement of the discharge through or over the dam is important.

There might be a minor price to pay for the release of water, because it normally would have been use for hydropower production. Negotiation with Statkraft SF is going on now.

The following data will be recorded in the tests:
- The pressure line in the filling
- Water-level upstream and downstream of the dam
- The discharge through the dam (measurd downstream of the dam)
- The water-level at the downstream edge of the dam_toe
- Picture from the test
- Video recording of the test.
- The development of the breach

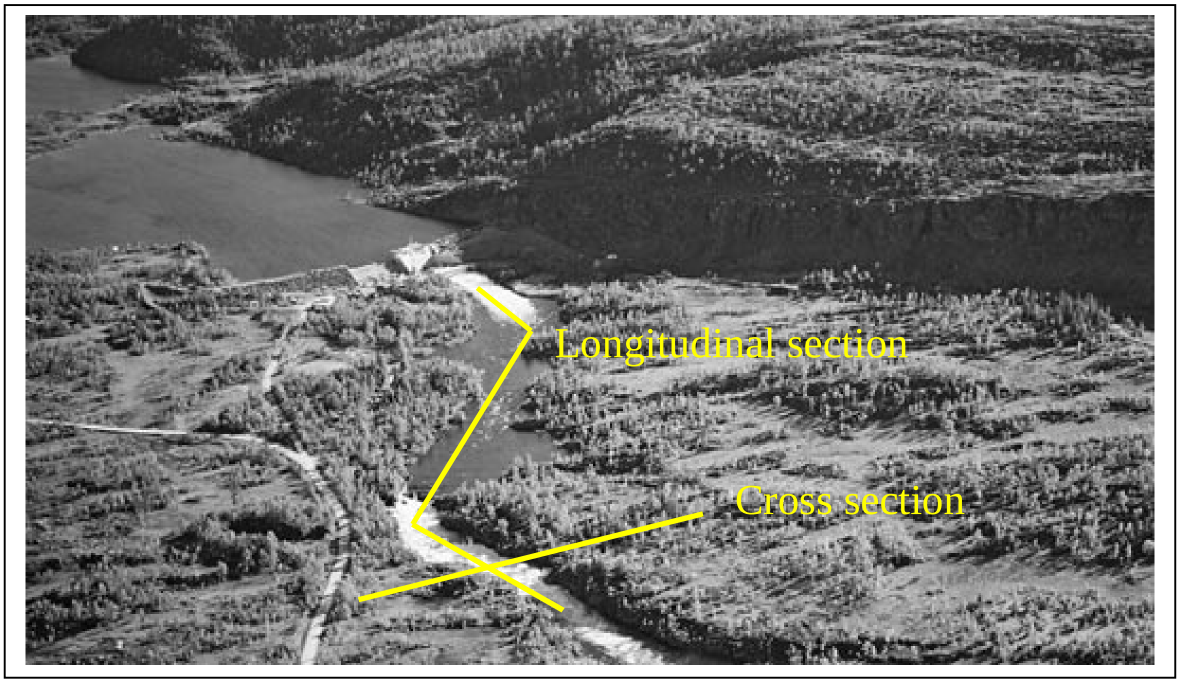


Figure 2 Overview of the test-area.

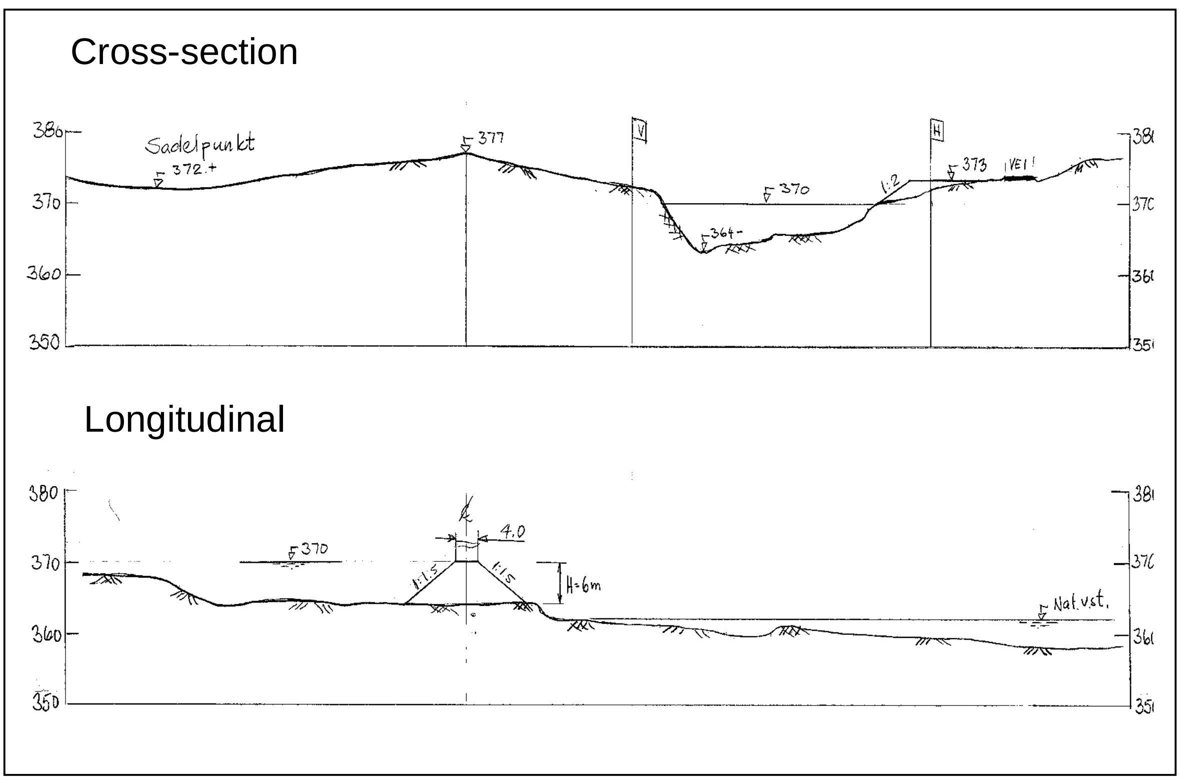


Figure 3. Cross-section and longitudinal section

5. BUDGET AND TIME SCHEDULE

The whole Norwegian project will run for 3 years with the startup the spring 2001 and with a total budget of 7 mill Norwegian Kroner. This close to 900 000 Euros.

6. PARTNERS

The Statkraft Grøner AS is the leader of the Norwegian project and also partner in IMPACT. The other Norwegian companies involved are:

- Norconsult AS
- NGI (Norwegian Geotechnical Institute)
- SINTEF Energy Research
- NTNU (Norwegian University for Science and Technology)

There is established advisory group or steering committee for the project in Norway. This group is made up of the major dam owners in Norway, NVE and the Norwegian Electricity Association EBL.

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