DAM and LEVEE BREACHING FORMULATIONS in U.S. ARMY CORPS OF ENGINEERS FINITE ELEMENT METHOD CODE ADAPTIVE HYDRAULICS – 2-DIMENSIONAL SHALLOW WATER MODULE

ENGINEER RESEARCH AND DEVELOPMENT CENTER, US ARMY CORPS OF ENGINEERS

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Executive Summary

This technical document and user manual presents the theory and application of Dam and Levee breaching formulations incorporated by Dynamic Solutions, LLC under U.S. Army Corps of Engineers (USACE) contract W912HZ-13-A-0006, Call 0002 (Task 2). The breaching formulations have been encoded within the Adaptive Hydraulics Code – 2 Dimensional Shallow Water Module (ADH) as a breaching library. This library consists of 7 formulations suitable for various dam/levee construction practices and sizes.

A breaching library consisting of 7 breaching formulations has been added to the 2D Shallow Water module of the USACE finite element code ADH. The formulations added into ADH are:

1. Johnson and Illes (1976) formulation, suitable for earth, gravity and arch concrete dams,
2. Singh and Snorrason (1982, 1974) formulation, suitable for earthen dams,
3. MacDonald and Langridge-Monopolis (1984) formulation, suitable for earthfill and non-earthfill dams
4. Froelich (1987, 1995) formulation, suitable for engineered earthen or slag dams,
5. Bureau of Reclamation (1988) formulation, suitable for earthen dams,
6. Von Thun and Gillette (1990) formulation, suitable for engineered dams with or without clay cores, and
7. Federal Energy Regulatory Commission, FERC (1987) formulation, suitable for engineered and nonengineered earthen and slag dams.

The implementation of these formulations has been tested within ADH and provided breach behavior expected from the formulations.

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1 INTRODUCTION

1.1 Objectives

The purpose of this work is to incorporate dam and levee breaching formulations in the 2-Dimensional Shallow Water ADH model.

This section of the report focuses on the breaching failure of dams and the methodologies utilized to predict the breach parameters of various types of dams such as earthen, concrete etc.

1.2 Types of Models for Dam Breaching

Per *Atallah (2002)* there are 2 distinct phases in modeling dam/levee breaching:

1. The prediction of breach parameters including side slope, shape, depth and width, and

2. The routing of the resultant flood wave downstream through the valley.

This report is primarily concerned with part 1 of the dam breach modeling process, i.e. prediction of dam breach parameters, and their encoding within the 2D ADH numerical finite element model.

1.3 Breach Parameters

Breach parameters are defined in disparate ways in literature; for the sake of clarity, this report defines breach parameters as follows:

a) Breach width (B_w): refers to the bottom width of the breach at breach completion

b) Breach depth (B_d) refers to the distance from the dam crest to the bottom of breach at breach completion

c) Breach initiation time (B_{t0}): refers to the time at which breach formation starts

d) Breach formation time (B_{tf}): refers to the time duration between breach initiation and breach completion.

1.4 Breach Formulations

1.4.1 Johnson and Illes

Johnson and Illes (1976) studied the failure of earthen, gravity, and arch concrete dams. They concluded that the breach width for an earthen and gravity dam is governed by the following regression relation:

$$0.5H_d < B_w < 3H_d$$

where H_d is the depth of water at the breach. They did not specify a relationship for arch concrete dams.

1.4.2 Singh and Snorrason

Singh and Snorrason (1982, 1984) studied the failure of 20 earthen and gravity dams, and created empirical relationships governing the breach widths. This relation for both earthen and gravity dams is governed by the following:

$$2H_d < B_w < 5H_d$$

and

$$0.25 < B_{tf} < 1$$

in hours.

1.4.3 MacDonald and Langridge-Monopolis

MacDonald and Mangridge-Monopolis (1984) studied the failure of 42 embankment dams and created relationships based on the volume of eroded embankment material. These relationships for an earthen embankment dams are expressed as:

$$V_{er} = 0.0261 * (V_0)^{0.769} * (H_d)^{0.769}$$

where V_{er} is the eroded embankment volume in cubic meters, V_0 is the reservoir volume in cubic meters, and

$$B_{tf} = 0.0179 * (V_{er})^{0364}$$

in hours.

For non-earthen embankment dams, the relationship is:

$$V_{er} = 0.0348 * (V_0)^{0.852} * (H_d)^{0.852}$$

The breach formation time (B_{tf}) is uncertain for non-earthen dams because their failure might occur due to structural failure instead of erosion of material. They recommended iterating on B_{tf} to get a range of failure parameters.

1.4.4 Froelich

Froelich (1987, 1995) performed non-dimensional analysis on 43 dam break cases and created formulations to estimate breach width, sideslopes and B_{tf}. The relationship for B_{tf} is expressed as:

$$B_{tf} = \frac{T_f}{(g * H_b)^{0.5}}$$

where T_f is a factor of reservoir storage and H_b is the height of the breach.

1.4.5 Bureau of Reclamation

Bureau of Reclamation (1988) developed breach width and breach formation time relations for earthen dams. These relations are expressed as:

$$B_w = 3H_w$$

where H_w is the breach height, and

$$B_{tf} = 0.011 * B_w$$

where B_{tf} is in hours and B_w is in meters.

1.4.6 Von Thun and Gillette

Von Thun and Gillette (1990) studied the data of *Froelich (1987)* and other researchers and developed breach parameters. Their breach parameters are given by:

$$B_w = 2.5H_w + C_b$$

where C_b is a coefficient dependent upon reservoir storage and H_w is the height of the breach.

The breach formation time is dependent upon the amount of erosion that occurs. The B_{tf} relations are expressed as:

$$B_{tf} = 0.020H_w + 0.25 \text{, Erosion resistant}$$

$$B_{tf} = 0.015H_w \qquad \text{, Easily erodible}$$

in hours

1.4.7 Federal Energy Regulatory Commission (FERC)

FERC (1987) proposed the following expressions for earthen, and slag or refuge dams:

$$2H_w < B_w < 4H_w$$

$$0.1 < B_{tf} < 1 \quad \text{, Engineered, compacted (in hours)}$$

$$0.1 < B_{tf} < 0.5 \quad \text{, Non-engineered, poorly compacted (in hours)}$$

2 ADH Shallow Water Breach Activation

Breach formulations within ADH have been implemented as a Breach library. This library is connected to ADH through a single file link, which is activated when the user specifies the breach boundaries described in the sections that follow.

In general the specification of a breach requires the user to specify 3 breach sections. These are the 2 side slopes and the central or main breach section through the designation of nodes strings, NDS (**Figure 1**).

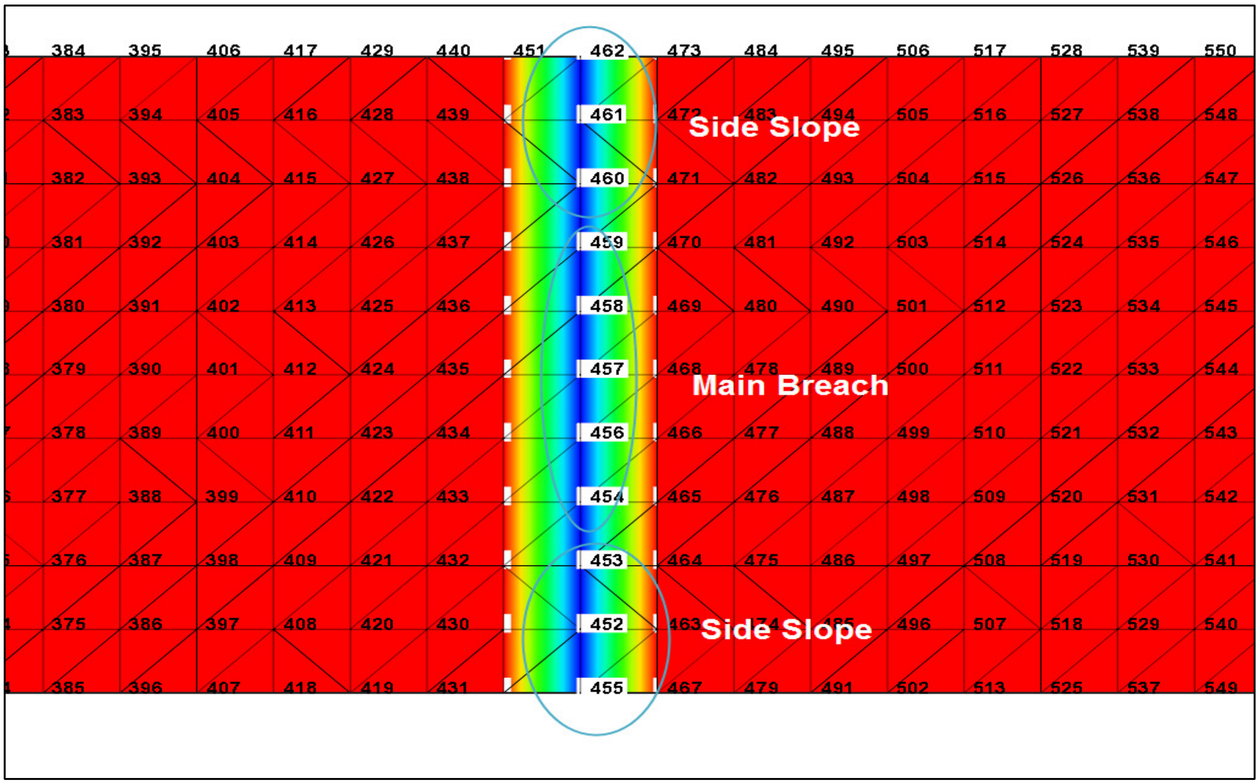

Figure 1: Side Slope and Main Breach

The NDS specification for the side slopes and main breach illustrated in Figure 1 are defined in **Figure 2**. The order of nodes or the order of the NDS strings is immaterial to the operation of breach parameters. The breach can be made triangular by the specification of just the side slopes, or it can be defined to be a rectangular breach by defining only the main breach, if the user chooses to do so.

```
! Side Slope Left Looking
! D/S from Dam/Levee
NDS 462 2
NDS 461 2
NDS 460 2

! Side Slope Right Looking
! D/S from Dam/Levee
NDS 455 3
NDS 452 3
NDS 453 3

! Main Breach Looking D/S
NDS 459 4
NDS 458 4
NDS 457 4
NDS 456 4
NDS 454 4
```

Figure 2: NDS Definitions for Side Slopes and Main Breach

2.1.1 *Johnson and Illes (JAI)*

Figures 3, 4 and 5 illustrate the parameters that are required to use the Johnson and Illes breaching formulation. **Table 1** defines the parameters of this formulation.

```
DB JAI 4 0 2000 2. 10 45000.
```

Figure 3: Specification of Main Breach using JAI Formulation

```
DB JAI 3 1 2000. 2 10.0 45000. 455 453
```

Figure 4: Specification of 1 Side Slope using JAI Formulation

```
DB JAI 2 1 2000. 2 10.0 45000. 462 460
```

Figure 5: Specification of 2nd Side Slope using JAI Formulation

Card	Explanation
DB	Dirichlet Boundary
JAI	Johnson and Illes
INTEGER	Node String
INTEGER	0, Main Breach 1, Side Slopes of the Breach
DOUBLE	Width of Main Breach, meters
DOUBLE	Minimum Breach Elevation, meters
DOUBLE	Dam/Levee Crest Elevation, meters
DOUBLE	Breach Failure Time, seconds
INTEGER	Node Farthest from Breach on Side Slope (not required for main breach)
INTEGER	Node Closest to Breach on Side Slope (not required for main breach)

Table 1: Card Properties for JAI Breach Formulation

2.1.2 Singh and Snorrason (SAS)

Figures 3, 4 and 5, and Table 1 also illustrate the parameters required for using *Singh and Snorrason* formulation in ADH. In Table 1, instead of JAI, the specification is SAS .The *Singh and Snorrason* formulation reaches complete breach failure at 3600 seconds, therefore the code will ignore any Breach failure time greater than 3600 in the parameter list.

2.1.3 MacDonald and Langridge-Monopolis (MLM)

The MLM formulation utilized in the breach library is for earthen embankment dams. **Figure 6** and **Table 2** describe the parameters required for using the MLM formulation.

```
DB MLM 4 400 1000 9.5 10

DB MLM 2 400 1000 9.5 10

DB MLM 3 400 1000 9.5 10
```

Figure 6: Specification for using MLM Formulation

Card	Explanation
DB	Dirichlet Boundary
MLM	MacDonald and Langridge-Monopolis
INTEGER	Node String
DOUBLE	Max Water Depth above Breach Bottom, meters
DOUBLE	Reservoir Volume, cubic meters
DOUBLE	Minimum Breach Elevation, meters
DOUBLE	Dam/Levee Crest Elevation, meters

Table 2: Card Properties for MLM Breach Formulation

2.1.4 Froelich (FRO)

Table 3 provides a list of parameters that must be specified to activate breaching using the *Froelich* (FRO) formulation.

Card	Explanation
DB	Dirichlet Boundary
FRO	Froelich
INTEGER	Node String
INTEGER	0, Main Breach 1, Side Slopes of the Breach
DOUBLE	Width of Main Breach, meters
DOUBLE	Minimum Breach Elevation, meters
DOUBLE	Dam/Levee Crest Elevation, meters
DOUBLE	Breach Failure Time, seconds
DOUBLE	Exponent (0.1-4) for the main breach, controls how fast the main breach progresses (only required on main breach)
INTEGER	Node Farthest from Breach on Side Slope (not required for main breach)
INTEGER	Node Closest to Breach on Side Slope (not required for main breach)

Table 3: Card Properties for FRO Breach Formulation

2.1.5 Bureau of Reclamation (BRC)

Figures 3, 4 and 5, and Table 1 also illustrate the parameters required for using BRC formulation in ADH. In table 1, instead of JAI, the specification is BRC. The user must ensure that the breach fail time specified follows the breach formation relationship in section *1.4.5.*

2.1.6 Von Thun and Gillette (VTG)

Figures 7, 8 and **Table 4** provide the parameters required for using the VTG formulation in ADH. The VTG formulation provides for describing the dam/levee as erodible or erosion resistant.

Card	Explanation
DB	Dirichlet Boundary
VTG	Von Thun and Gillette
INTEGER	Node String
INTEGER	0, Main Breach 1, Side Slopes of the Breach
DOUBLE	Width of Main Breach, meters
DOUBLE	Minimum Breach Elevation, meters
DOUBLE	Dam/Levee Crest Elevation, meters
INTEGR	0, Easily Erodible 1, Erosion Resistant
DOUBLE	Breach Failure Time, seconds
INTEGER	Node Farthest from Breach on Side Slope (not required for main breach)
INTEGER	Node Closest to Breach on Side Slope (not required for main breach)

Table 4: Card Properties for VTG Breach Formulation

```
DB VTG 4 0 3000 2 10 1 8000.
```

Figure 7: Specification for Using VTG Formulation on Main Breach

```
DB VTG 2 1 3000. 2 10.0 1 8000. 462 460

DB VTG 3 1 3000. 2 10.0 1 8000. 455 453
```

Figure 8: Specification for Using VTG Formulation on Side Slopes

2.1.7 Federal Energy Regulatory Commission (FERC)

Figures 9, 10 and **Table 5** provide the parameters required for using the VTG formulation in ADH. The VTG formulation provides for describing the dam/levee as engineered/well compacted and non-engineered/poorly compacted.

Card	Explanation
DB	Dirichlet Boundary
FER	FERC
INTEGER	Node String
INTEGER	0, Main Breach 1, Side Slopes of the Breach
DOUBLE	Width of Main Breach, meters
DOUBLE	Minimum Breach Elevation, meters
DOUBLE	Dam/Levee Crest Elevation, meters
INTEGR	0, Non-Engineered 1, Engineered/Well Compacted
DOUBLE	Breach Failure Time, seconds
INTEGER	Node Farthest from Breach on Side Slope (not required for main breach)
INTEGER	Node Closest to Breach on Side Slope (not required for main breach)

Table 5: Card Properties for VTG Breach Formulation

2.2.1 Testing and Results

Breaching formulations in ADH were tested on rectangular grid 50000m long and 5000m wide (**Figure 9**). The dam crest elevation was specified as 10 m , the breach minimum elevation as 2m, the main breach width was 3000m, and the breach failure time was specified as 5000 sec. All 7 breaching formulations encoded within the breach library were tested. **Figures 10, 11 and 12** illustrate the breach shape computed by ADH at 4000 seconds for the different formulations.

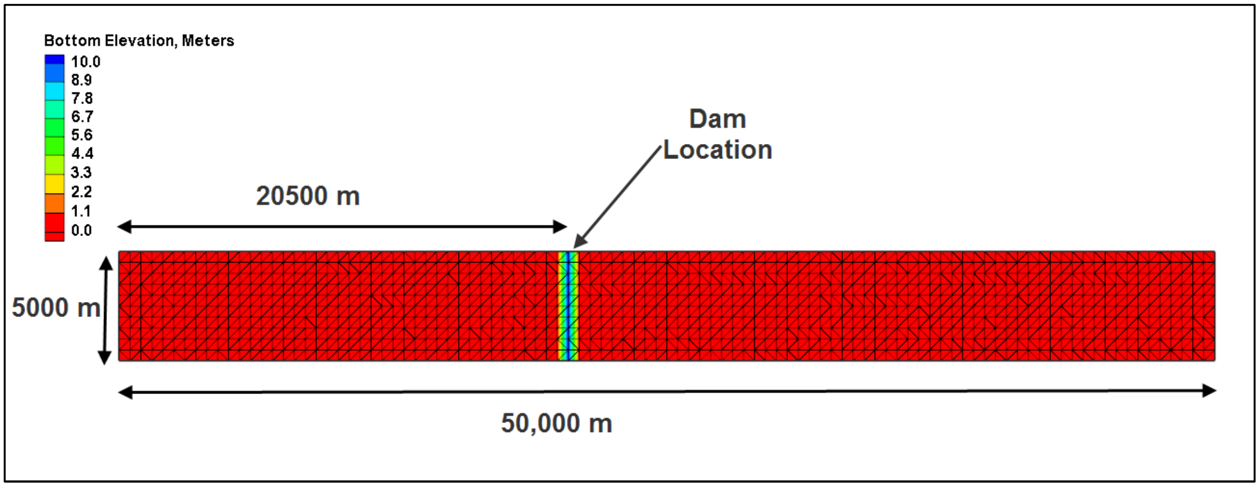

Figure 9: Breach Test Domain

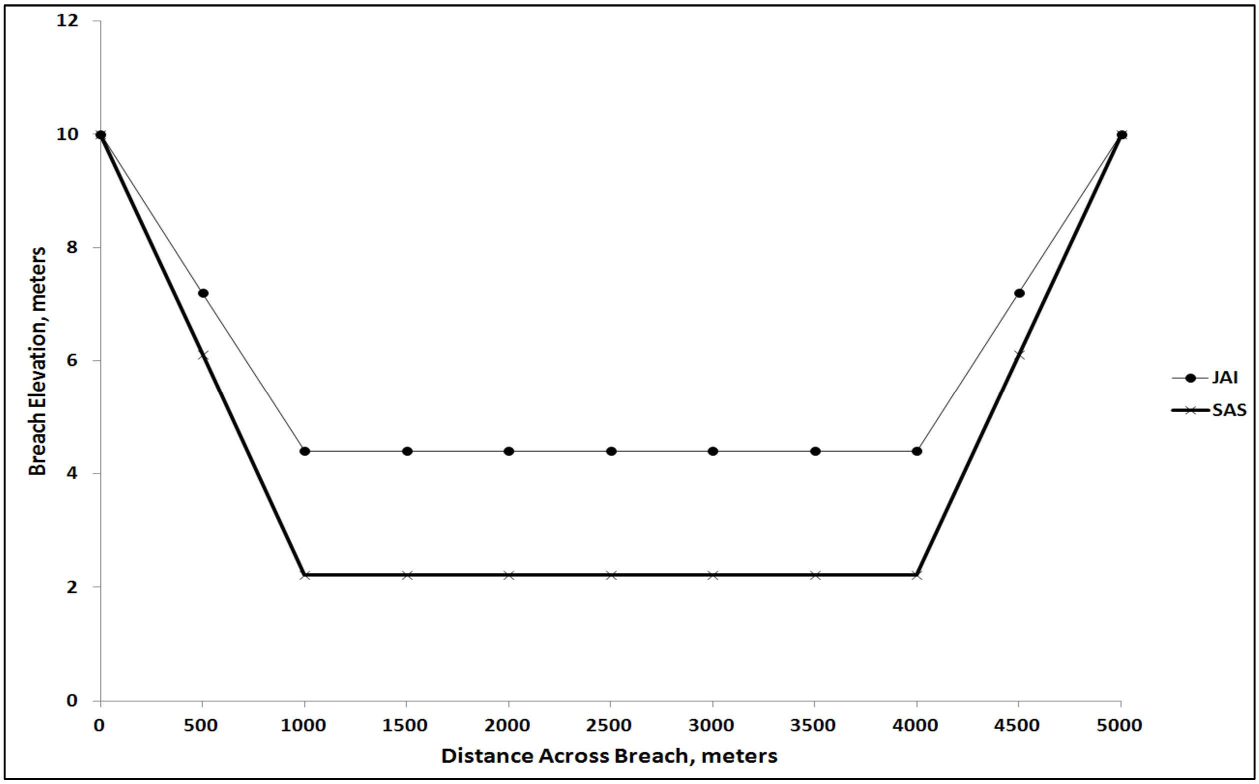

Figure 10: Breach Shape for JAI and SAS Breach Formulations at 4000 seconds

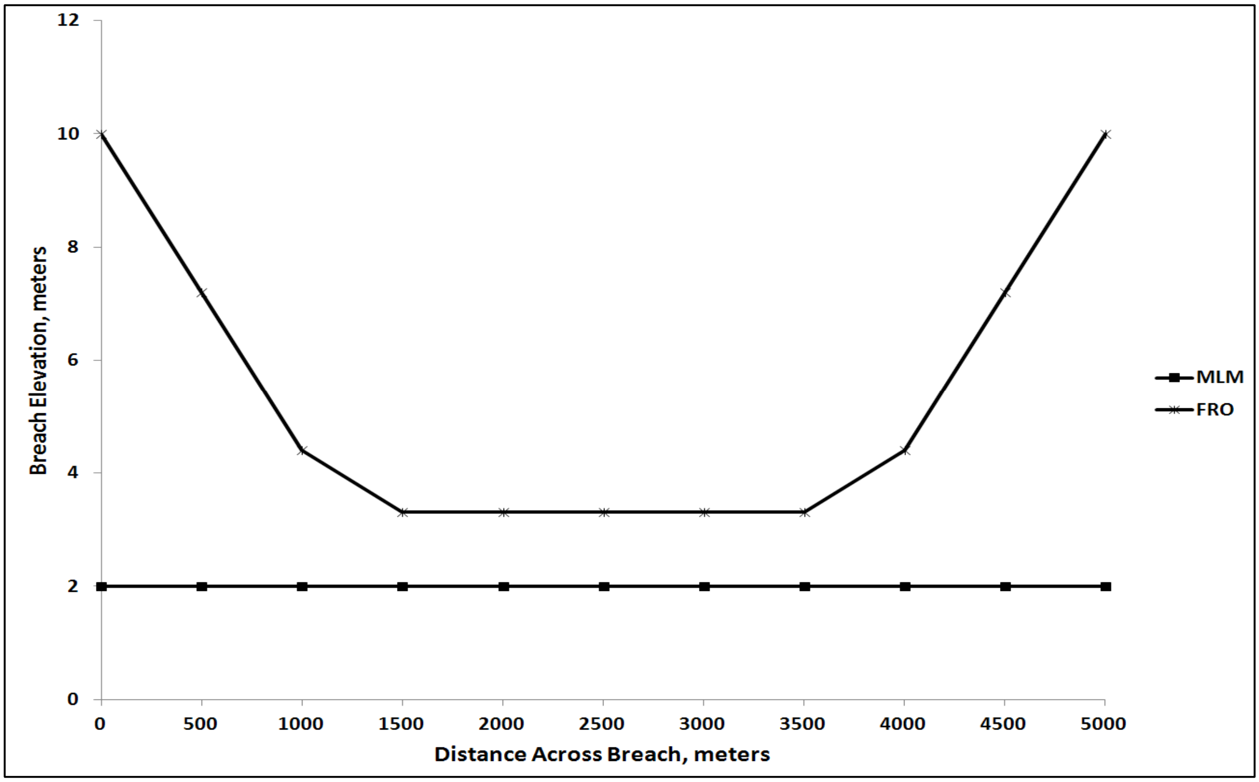

Figure 11: Breach Shape for MLM and FRO Formulations at 4000 seconds

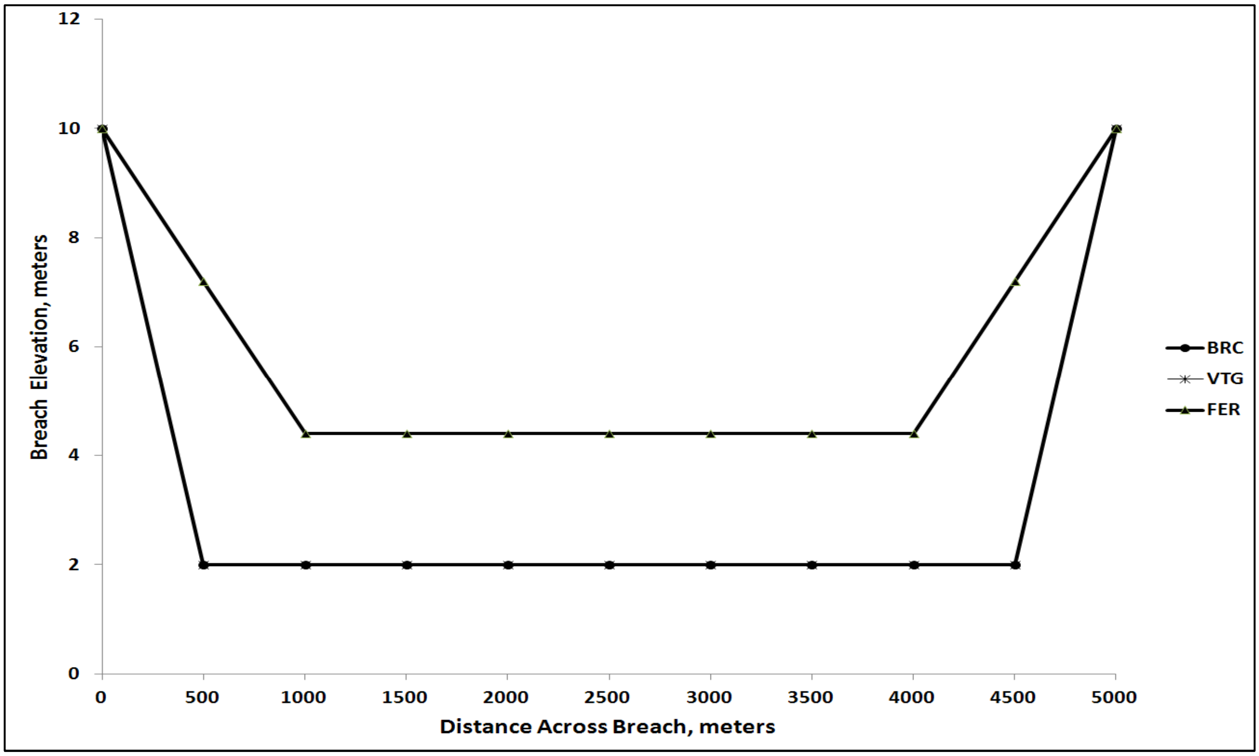

Figure 12: Breach Shape for FER, VTG and BRC Breach Formulations at 4000 seconds

3 CONCLUSIONS

A breaching library consisting of 7 breaching formulations has been added to the 2D Shallow Water module of the USACE finite element code ADH. The formulations added into ADH are:

1. Johnson and Illes (1976) formulation, suitable for earth, gravity and arch concrete dams,
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The implementation of these formulations has been tested within ADH and provided breach behavior expected from the formulations.

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