Documentation of Initial Hazard Potential Classification Assessment

East Ash Pond
Joppa Power Station
Massac County, Illinois

Stantec Consulting Services Inc.
Design with community in mind
www.stantec.com

Prepared for:
Dynegy
October 12, 2016

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Executive Summary

This report documents the hazard potential classification assessment for the East Ash Pond at the Joppa Power Station as required per the CCR Rule in 40 C.F.R. § 257.73-(a)(2). The applicable hazard potential classifications are defined in 40 C.F.R. § 257.53 as follows:

> (1) High hazard potential CCR surface impoundment means a diked surface impoundment where failure or mis-operation will probably cause loss of human life.
>
> (2) Significant hazard potential CCR surface impoundment means a diked surface impoundment where failure or mis-operation results in no probable loss of human life, but can cause economic loss, environmental damage, disruption of lifeline facilities, or impact other concerns.
>
> (3) Low hazard potential CCR surface impoundment means a diked surface impoundment where failure or mis-operation results in no probable loss of human life and low economic and/or environmental losses. Losses are principally limited to the surface impoundment owner's property.

Based on these definitions and the analysis herein, the East Ash Pond is classified as a High hazard potential CCR surface impoundment.

This report contains supporting documentation for the hazard potential classification assessment. The hazard potential classification for this CCR unit was determined by a breach analysis conducted by Stantec in August, 2016.

1. Introduction

1.1. Background

The CCR Rule was published in the Federal Register on April 17, 2015. The Rule requires that a hazard potential classification assessment be performed for existing CCR surface impoundments that are not incised. A previously completed assessment may be used in lieu of the initial assessment provided the previous hazard assessment was completed no earlier than April 17, 2013. The applicable hazard potential classifications are defined in the CCR Rule 40 C.F.R. § 257.53 as follows:

High Hazard Potential CCR surface impoundment means a diked surface impoundment where failure or mis-operation will probably cause loss of human life.

Significant Hazard Potential CCR surface impoundment means a diked surface impoundment where failure or mis-operation results in no probable loss of human life, but can cause economic loss, environmental damage, disruption of lifeline facilities, or impact other concerns.

Low Hazard Potential CCR surface impoundment means a diked surface impoundment where failure or mis-operation results in no probable loss of human life and low economic and/or environmental losses. Losses are principally limited to the surface impoundment owner's property.

Dynegy has contracted Stantec Consulting Services Inc. (Stantec) to prepare hazard potential classification assessments for selected impoundments[1].

It was determined that there was no existing available hazard potential classification assessment documentation for the East Ash Pond.

1.2. Location

The Joppa Power Station is located in Massac County, Illinois approximately 18 miles downstream of the confluence of the Tennessee River and the Ohio River. The plant is located on the northern bank of the Ohio River, adjacent to the village of Joppa. The East Ash Pond is located to the north of the main facility. The project site overview can be seen in Figure 1.

[1] Dynegy Administrative Services Company (Dynegy) contracted Stantec on behalf of the Joppa Power Station owner, Electric Energy, Inc. Thus, Dynegy is referenced in this report.

Figure 1 Site Overview

2. Source Data

The following information was used to perform the hazard assessment of the East Ash Pond:

- 2012 Digital Elevation Model (DEM) obtained from Illinois Height Modernization (ILHMP) Program for Massac County
- Imagery from Bing Maps
- 1-foot contours provided by Dynegy, developed from 2015 Survey and Bathometric data
- 2011 National Land Cover Data obtained from National Land Cover Database (NLCD 2011) Multi-Resolution Land Characteristics (MRLC) Consortium
- Wapora, Inc., "Proposed East Ash Pond Effluent pH Control Tank", Electric Energy, Inc., Dynegy File: 00651 PDF, December 27, 1972

- Brown, Hoffmann & Roberts, Inc., "Ash Lagoon Overflow – Cover Sheet, Plan/Profile, Cross-sections, and Detail Sheet", Electric Energy, Inc., Dynegy File: 02199 Sheet 1-8, April 27, 1992

- Wapora, Inc., "Proposed East Ash Pond", Electric Energy, Inc., Dynegy File: 4229-08200 PDF, December 7, 1972

- Wapora, Inc., "East Ash Pond Sulfuric Acid Storage Tanks and pH Control System", Electric Energy, Inc., Dynegy File: 4229-08212 PDF, May 24, 1973

- Wapora, Inc., "East Ash Pond Plan, Sections and Details", Electric Energy, Inc., Dynegy File: 4229-08218 PDF, June 22, 1973

- Wapora, Inc., "East Ash Pond Sulfuric Acid Storage Tanks and pH Control System Plan, Sections and Details", Electric Energy, Inc., Dynegy File: 4229-08221 PDF, July 3, 1973

3. Potential Failure Scenarios

3.1. Facility Description

The East Ash Pond has a surface area of approximately 103 acres with approximately 32 acres holding water. The remaining area contains coal combustion residuals (CCR). The maximum embankment height is approximately 45 feet. The crest of the pond is at approximate elevation 380 feet with a normal pool of approximately 374 feet. There is a 24 inch diameter corrugated metal pipe (CMP) through the central dike that connects the northern section and southern section to manage flow between the sections, which is not controlled. The southern section's primary outlet structure is a 24 inch diameter steel "T" structure connected to a 24 inch diameter pipe that passes through the eastern embankment. The northern section discharges through a 30 inch diameter pipe that passes through the most northern embankment. Flow from the pond discharges to an open channel then through a concrete culvert under the Station's coal-delivery railroad before discharging into the Ohio River 2,400 feet downstream of the railroad.

3.2. Failure Scenarios

3.2.1. PMP Scenario

The breach scenario evaluated for the East Ash Pond was a piping breach during the Probable Maximum Precipitation (PMP) event. The East Ash Pond is perched and inflow from storm events would consist of rainfall falling directly on the pond. The freeboard for the pond is greater than the PMP volume, therefore the pool elevation for the breach scenario was the normal pool plus the volume of the PMP event (38 inch depth across a 103 acre footprint). Since the PMP event does not overtop the crest of the East Ash Pond, a piping breach was evaluated instead of an overtopping breach.

3.2.2. Breach Locations

Six breach locations were selected around the East Ash Pond. These locations include: one to the north, two breaches to the west, one breach to the south and two breaches to the east. The six breach scenarios can be seen in Figure 2. Breach locations were selected to evaluate inundation at representative and reasonable breach locations at which a failure might occur.

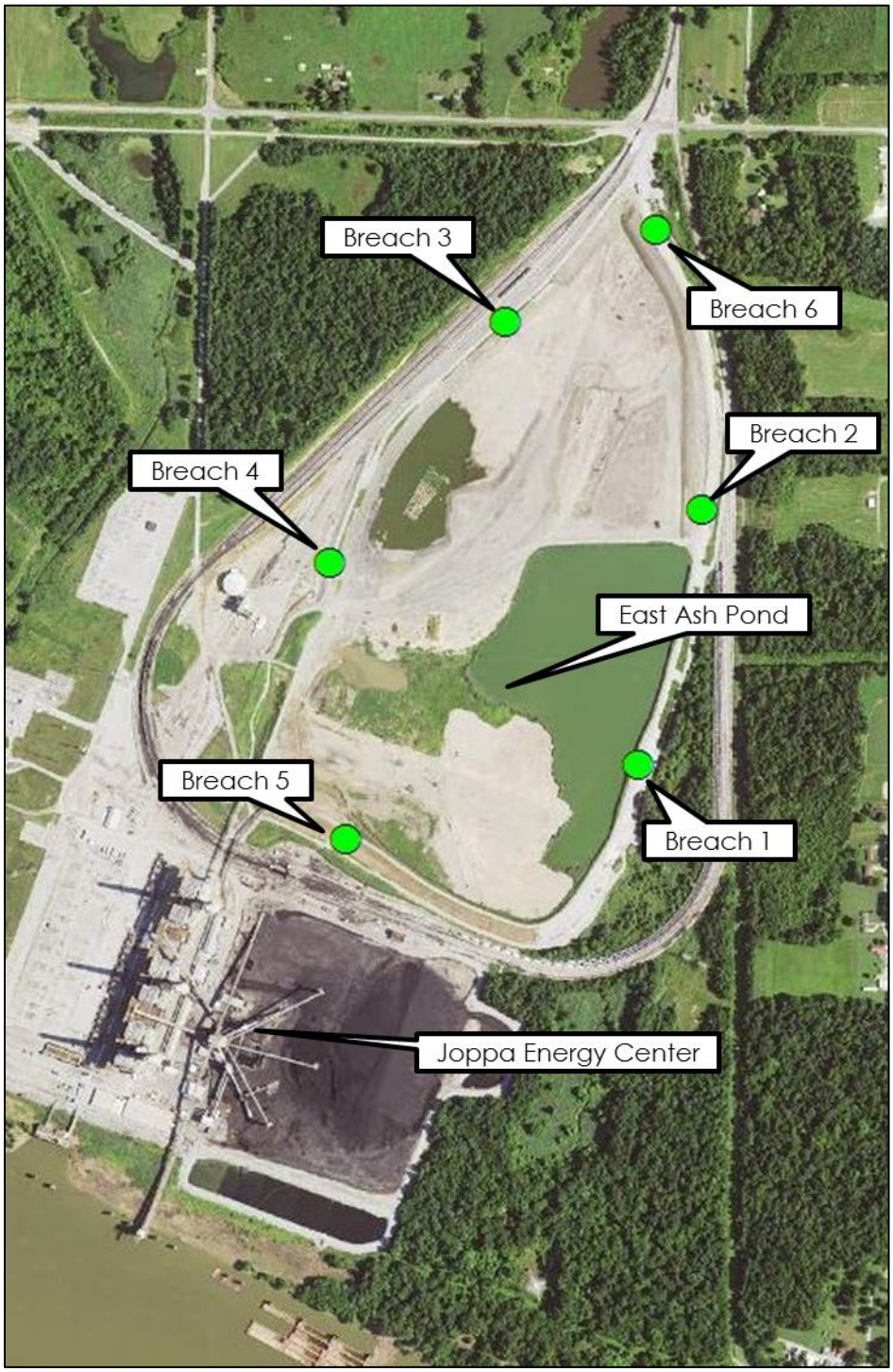

Figure 2 Joppa East Ash Pond Breach Locations

3.3. Breach Parameter Development

The breach function of HEC-RAS 5.0.1 requires input of estimated breach parameters and impounded volumes. Breach parameters were determined using empirical equations. Since there is uncertainty in predicting dam breach parameters, Stantec used several empirical equations and based final breach parameters on the average of the estimates and engineering judgment (References 3 - 11).

Table 1 summarizes the breach parameters estimated for this analysis. These values are based on the assumed failure conditions, height of breach, impoundment water volume above breach, and width of the embankment. The empirical calculations that served as the basis for the breach parameters' estimation are included in Appendix A.

Based on visual inspection of aerials as well as information from the EPA Dam Safety Assessment of CCW Impoundments Joppa Plant report (Reference 2), the north section of the East Ash Pond appears to be a dry stack of CCR. The EPA report (Reference 2) also states that the East Ash Pond has CCR that consists of bottom ash and fly ash, with the northern section being drained. There is a 24 inch diameter CMP connecting the northern and southern sections of the pond that is uncontrolled. Due to uncertainty of the sub layers within the pond and water quantity within the stack of CCR, the breach bottom elevation was set to the toe elevation of the embankment. Setting the breach bottom elevation to the toe of the embankment resulted in conservative breach scenarios.

Table 1 Breach Modeling Parameters for East Ash Pond

Breach Scenario	Pool Elevation at Start of Breach (feet)	Breach Bottom Elevation (feet)	Breach Bottom Width (feet)	Breach Side Slopes (Horizontal : Vertical)	Breach Development Time (hour)
"PMP – Pipe Penetration" Breach Scenario - 1	379.5	333	47.0	0.9	0.41
"PMP – Pipe Penetration" Breach Scenario - 2	379.5	357	57.3	0.9	0.77
"PMP – Pipe Penetration" Breach Scenario - 3	379.5	360	57.9	0.9	0.88

Breach Scenario	Pool Elevation at Start of Breach (feet)	Breach Bottom Elevation (feet)	Breach Bottom Width (feet)	Breach Side Slopes (Horizontal : Vertical)	Breach Development Time (hour)
"PMP – Pipe Penetration" Breach Scenario - 4	379.5	362	58.2	0.9	0.97
"PMP – Pipe Penetration" Breach Scenario - 5	379.5	355	56.7	0.9	0.72
"PMP – Pipe Penetration" Breach Scenario - 6	379.5	350	55.0	0.9	0.61

A stage-storage curve for the pond was developed based on 1-foot contours, Light Detection and Ranging (LiDAR) and record drawings provided by Dynegy. The elevations and volumes that were calculated for input into the HEC-RAS model storage basin are listed in Table 2.

Table 2 Elevation Storage Data for Ash Pond

Elevation (NAVD88)	Cumulative Volume (Acre-feet)
333	0
335	3.9
340	31.5
345	74.0
350	131.6
355	203.7
360	288.1
365	384.9
370	498.8
375	697.2
380	1076.8

3.4. Hydraulic Model Development

For breach inundation modeling, Stantec used the United States Army Corps of Engineers (USACE) Hydrologic Engineering Center River Analysis System (HEC-RAS), version 5.0.1, computer program to perform hydraulic routing calculations. The HEC-RAS breach simulation was configured as an unsteady flood routing model. A two-dimensional flood routing model was selected for simulating potential breach

impacts along the embankment of the East Ash Pond. A breach from the embankment to the north, west or south would travel in multiple flow directions following the topography of the land while a breach to the east would travel in a concentrated flow direction through a natural valley towards the Ohio River.

3.4.1. Digital elevation model (DEM)

A database of elevations for the area to be modeled, known as a digital elevation model (DEM), was constructed using Geographic Information System (GIS) software, ERSI ArcGIS 2015. The DEM utilized a raster format of LiDAR data obtained from the Illinois Height Modernization (ILHMP) Program for Massac County Illinois. The LiDAR data was referenced to the North American Vertical Datum of 1988 (NAVD88) and using the North American Datum of 1983 (in feet) with Illinois State Plane East projection. The dataset has an accuracy of 0.3 feet vertically and a horizontal positional accuracy of 2.8 feet.

3.4.2. Mesh

HEC-RAS 5.0.1 utilizes a mesh based solver which requires the user to create a fixed Cartesian grid of equal x and y dimensions. The program then creates orthogonal mesh cells along the 2D boundary resulting in a hybrid mesh. HEC-RAS 5.0.1 has the capability of using large computational mesh spacing. A mesh cell size of 50 feet was used in this application since it effectively captured the important features of the DEM.

3.4.3. Material Cover

Land use files were obtained from the National Land Cover Data Set (2011) and utilized to develop a spatial reference for Manning's roughness values to be applied to the numerical model. Aerial imagery was compared to the land use files to verify that Manning's roughness values reflected current conditions.

Land cover GIS files were imported into HEC-RAS from ArcGIS with corresponding Manning's values. The Manning's "n" values were determined using past hydraulic models and engineering judgment. The GIS land cover file was converted to a GeoTiff file so that HEC-RAS could read in the data and apply the roughness value to the mesh cells. A table of Manning's "n" values to corresponding land cover can be seen in Table 3.

Table 3 Manning's Roughness Values

Land Cover Type	Manning's "n" Value
Barren Land	0.020
Cultivated Crops	0.045
Deciduous Forest	0.120
Developed, Low Intensity	0.060
Developed, Medium Intensity	0.080

Land Cover Type	Manning's "n" Value
Developed, High Intensity	0.100
Developed, Open Space	0.040
Emergent Herbaceous Wetlands	0.100
Open Water	0.035
Pasture/Hay	0.035
Woody Wetlands	0.060

3.4.4. Break Lines

Break lines were created within HEC-RAS to capture important features of the DEM. These break lines force cell faces to align along features such as roadways, railways, or levees in the DEM, allowing critical features to be captured in the model mesh. This process was especially important for the railroad that travels around the east and south of the East Ash Pond. A break line was created along the centerline of the railroad, surrounding roadways and Old Ash Pond embankment.

3.4.5. SA/2D Model Connections

The outflow location (embankment breach area) was connected to the 2D flow area (floodplain) using a SA/2D connection. The SA/2D connection was located along the East Ash Pond embankment, typically at the top of crest of the embankment in six different breach locations. A weir coefficient of 2.6 was applied to the breach because this is the HEC-RAS default value for earth dams.

3.4.6. Boundary Conditions

The downstream boundary conditions for the 2D portion of the model were set to normal depth, which utilized the average slope of the channel/topography throughout the model. All breach simulations used a 2D boundary condition of normal depth with a slope of 0.005.

3.5. Breach Modeling Results

Inundation limits for each of the breach scenarios were evaluated to determine the potential impacts on property and structures and the potential risk to human life. Faster moving water creates greater risk for damage to infrastructure and greater chance of loss of life; according to the National Flood Insurance Program (NFIP), water moving at more than five feet per second is considered to be moving with high velocity (Reference 12).

Analyses indicate that a potential breach of the East Ash Pond results in depths greater than two feet and velocities greater than or equal to five feet per second impacting occupied structures nearby the East Ash Pond. The analyses indicate that a failure of the East Ash Pond's east embankment will discharge into the low area to the east of Joppa Power Station reaching within approximately 400 feet of Joppa

High School. Breaches of the East Ash Pond west and south embankments mainly affect Joppa Power Station. A breach to the north would affect the properties to the north of the pond across County Road 1000 N. In the breach scenarios evaluated, discharge eventually flows to the Ohio River. Table 4 below shows the breach results for the selected areas surrounding the East Ash Pond along with the number of impacted structures.

Table 4 Area of Interest Breach Results

Area of Interest Relative to East Ash Pond	# of Impacted Structures	Maximum Flood Depth (feet)	Maximum Flood Velocity (feet/sec)
North	2	>2	>5
East	4	>2	>5
West	1	>3	>=5
South	1	>4	>5

4. Hazard Classification

Areas of potential impact were identified with results discussed in Section 3.5 of this report. Based on these results, it is Stantec's opinion that a breach of the East Ash Pond represents a probable threat to human life. Therefore, the impoundment fits the definition for a High hazard potential CCR surface impoundment (as defined in the CCR Rule §257.53) (Reference 1).

5. References

1. US Environmental Protection Agency. (2015). *Disposal of Coal Combustion Residuals from Electric Utilities, 40 CFR § 257 and § 261* (effective April 17, 2015).

2. US Environmental Protection Agency. (2010). *Dam Safety Assessment of CCW Impoundments Joppa Plant,* Prepared by O'Brien & Gere Engineers, Inc. (dated September 24, 2010).

3. Johnson, F.A and Illes, P. (1976). "A Classification of Dam Failures." *Water Power Dam Construction,* 28, 43-45.

4. Singh, Krishan P. and Snorrason, A. (1982*). SWS Contract Report 288: Sensitivity of Outflow Peaks and Flood Stages to the Selection of Dam Breach Parameters and Simulation Models*. Illinois Department of Energy and Natural Resources, State Water Survey Division.

5. Singh, Krishan P. and Snorrason, A. (1984*).* "Sensitivity of Outflow Peaks and Flood Stages to the Selection of Dam Breach Parameters and Simulation Models." *Journal of Hydrology*, 68, 295-310.

6. MacDonald, T. C., and Langridge-Monopolis, J. (1984). "Breaching Characteristics of Dam Failures." *Journal of Hydraulic Engineering*, 110 (5), 567-586.

7. Federal Energy Regulatory Commission (FERC). (1987). *FERC 0119-1: Engineering Guidelines for the Evaluation of Hydropower Projects*. Office of Hydropower Licensing.

8. Froehlich, D. C. (1987). "Embankment Dam Breach Parameters." *Proceedings of the 1987 National Conference on Hydraulic Engineering*, ASCE, Williamsburg Virginia, 570-575.

9. US Bureau of Reclamation (USBR). (1988). *ACER Technical Memorandum No. 11: Downstream Hazard Classification Guidelines*. Assistant Commissioner-Engineering and Research, Denver, Colorado, 57.

10. Von Thun, Lawrence J. and D. R. Gillette. (1990). *Guidance on Breach Parameters*, unpublished internal document, USBR, Denver, Colorado, 17. (Referenced in Wahl 1998).

11. Froehlich, D. C. (1995). "Embankment Dam Breach Parameters Revisited." *Proceedings of the 1995 ASCE Conference on Water Resources Engineering*, ASCE, San Antonio, Texas, 887-891.

12. Federal Emergency Management Association (FEMA). (2004). *Hazard Potential Classification System for Dams.*

Appendix A

Breach Parameters

Dam Breach Parameter Estimation
Earthen Embankment Comparative Spreadsheet

Project Data:

Dam: *Joppa - Ash Pond*
Location: *Joppa, Illinois*
Notes: *"PMP" Breach of Embankment - Breach Location 1*
Piping Failure Assumed

Inputs:

		English Units		*SI Units*	
Height of dam	h_d	47.0	feet	14.3	meters
Height of breach	h_b	47.0	feet	14.3	meters
Height/depth of water during breach	h_w	46.5	feet	14.2	meters
Storage	S	1077.0	ac-feet	1328459.9	m^3
Volume of water at breach	V_w	1077.0	ac-feet	1328459.9	m^3
Width of dam at base	W_{base}	100.0	feet	30.5	meters
Width of dam at crest	W_{crest}	30.0	feet	9.1	meters
Estimated breach side slope	Z	1.0		1.0	
Baseflow	Q_{base}	0.0	ft^3/s	0.00	m^3/s
Type of Failure		Piping			
Dam has core wall?		No			
Erosion resistant embankment?		No			

Data Convention:
- User Input Data
- Default calculation, user can
- Calculated value.
- Adj. value

Froelich '95 Calculated Values:		**Froelich '95 Calculated Values:**				**Average Calculated Values:**			
Breach width	B_{AVG}	89.3	feet	27.2	meters	126.7	feet	38.6	meters
Breach bottom width	B_W	47.0	feet	14.3	meters	89.4	feet	27.3	meters
Breach formation time	t_f	0.41	hours	0.41	hours	0.41	hours	0.41	hours
Peak discharge	Q_p	36,768	ft^3/s	1041.2	m^3/s	74,036	ft^3/s	2096.6	m^3/s
Breach side slope	Z	0.90		0.90		0.79		0.79	
Volume of embankment eroded	V_{er}	273119.4	ft^3	7734.2	m^3	387,189	ft^3	10,964	m^3
Volume of water discharged	V_o,V_{out}	1077.00	ac-feet	1328459.9	m^3	1077.0	ac-feet	1,328,460	m^3

Estimates of Breach Width & Dimensions

Source Equation (See Attached Equation Reference)	**B** (m)	**B** (ft)	**Z**	**V_{er}** (m^3)	**K_o**	$\overline{W}$ (m)	K_c	**C_b**
1 - Johnson and Illes 1976	25.1	82.3						
2 - Singh and Snorrason 1982, 1984	50.2	164.5						
3 - MacDonald and Langridge-Monopolis 1984	36.1	118.5		10257.9				
4 - MacDonald and Langridge-Monopolis 1984			0.500					
5 - FERC 1987	43.0	141.0						
6 - FERC 1987			0.625					
7 - Froehlich 1987	31.0	101.8			1.0			
8 - Froehlich 1987			0.934			19.8	1.0	
9 - USBR 1988	42.5	139.5						
10 - Von Thun and Gillette 1990			1.000					
11 - Von Thun and Gillette 1990	53.7	176.3						18.3
12 - Froehlich 1995	27.2	89.3			1.0			
13 - Froehlich 1995			0.900					

Dam Breach Parameter Estimation
Earthen Embankment Comparative Spreadsheet

Project Data:

Dam: *Joppa - Ash Pond*
Location: *Joppa, Illinois*
Notes: *"PMP" Breach of Embankment - Breach Location 1*
Piping Failure Assumed

Inputs:

		English Units		*SI Units*	
Height of dam	h_d	47.0	feet	14.3	meters
Height of breach	h_b	47.0	feet	14.3	meters
Height/depth of water during breach	h_w	46.5	feet	14.2	meters
Storage	S	1077.0	ac-feet	1328459.9	m^3
Volume of water at breach	V_w	1077.0	ac-feet	1328459.9	m^3
Width of dam at base	W_{base}	100.0	feet	30.5	meters
Width of dam at crest	W_{crest}	30.0	feet	9.1	meters
Estimated breach side slope	Z	1.0		1.0	
Baseflow	Q_{base}	0.0	ft^3/s	0.00	m^3/s
Type of Failure		Piping			
Dam has core wall?		No			
Erosion resistant embankment?		No			

Data Convention:
- User Input Data
- Default calculation, user can
- Calculated value.
- Adj. value

Froelich '95 Calculated Values:		**Froelich '95 Calculated Values:**				**Average Calculated Values:**			
Breach width	B_{AVG}	89.3	feet	27.2	meters	126.7	feet	38.6	meters
Breach bottom width	B_W	47.0	feet	14.3	meters	89.4	feet	27.3	meters
Breach formation time	t_f	0.41	hours	0.41	hours	0.41	hours	0.41	hours
Peak discharge	Q_p	36,768	ft^3/s	1041.2	m^3/s	74,036	ft^3/s	2096.6	m^3/s
Breach side slope	Z	0.90		0.90		0.79		0.79	
Volume of embankment eroded	V_{er}	273119.4	ft^3	7734.2	m^3	387,189	ft^3	10,964	m^3
Volume of water discharged	V_o,V_{out}	1077.00	ac-feet	1328459.9	m^3	1077.0	ac-feet	1,328,460	m^3

Estimates of Failure Time

Source Equation (See Attached Equation Reference)	t_f (hours)
14 - Singh and Snorrason 1982, 1984	0.625
15 - MacDonald and Langridge-Monopolis 1984	0.516
16 - FERC 1987	0.550
17 - Froehlich 1987	0.469
18 - USBR 1988	0.300
19 - Von Thun and Gillette 1990	
20 - Von Thun and Gillette 1990	
21 - Von Thun and Gillette 1990	0.213
22 - Von Thun and Gillette 1990	0.231
23 - Froehlich 1995	0.407

Dam Breach Parameter Estimation
Earthen Embankment Comparative Spreadsheet

Project Data:

Dam: *Joppa - Ash Pond*
Location: *Joppa, Illinois*
Notes: *"PMP" Breach of Embankment - Breach Location 1*
Piping Failure Assumed

Inputs:

		English Units		*SI Units*	
Height of dam	h_d	47.0	feet	14.3	meters
Height of breach	h_b	47.0	feet	14.3	meters
Height/depth of water during breach	h_w	46.5	feet	14.2	meters
Storage	S	1077.0	ac-feet	1328459.9	m^3
Volume of water at breach	V_w	1077.0	ac-feet	1328459.9	m^3
Width of dam at base	W_{base}	100.0	feet	30.5	meters
Width of dam at crest	W_{crest}	30.0	feet	9.1	meters
Estimated breach side slope	Z	1.0		1.0	
Baseflow	Q_{base}	0.0	ft^3/s	0.00	m^3/s
Type of Failure		Piping			
Dam has core wall?		No			
Erosion resistant embankment?		No			

Data Convention:
- User Input Data
- Default calculation, user can
- Calculated value.
- Adj. value

Froelich '95 Calculated Values:		**Froelich '95 Calculated Values:**				**Average Calculated Values:**			
Breach width	B_{AVG}	89.3	feet	27.2	meters	126.7	feet	38.6	meters
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Breach formation time	t_f	0.41	hours	0.41	hours	0.41	hours	0.41	hours
Peak discharge	Q_p	36,768	ft^3/s	1041.2	m^3/s	74,036	ft^3/s	2096.6	m^3/s
Breach side slope	Z	0.90		0.90		0.79		0.79	
Volume of embankment eroded	V_{er}	273119.4	ft^3	7734.2	m^3	387,189	ft^3	10,964	m^3
Volume of water discharged	V_o,V_{out}	1077.00	ac-feet	1328459.9	m^3	1077.0	ac-feet	1,328,460	m^3

Estimates of Peak Discharge

Source Equation (See Attached Equation Reference)	**Q_p (m^3/s)**	**Q_p (ft^3/s)**	η	**k**	**d**
24 - Kirkpatrick 1977	1011.1	35,680			
25 - SCS 1981	2241.5	79,095			
26 - Hagen 1982	2356.0	83,138			
27 - USBR 1982	2579.0	91,007			
28 - Singh and Snorrason 1984	2052.9	72,442			
29 - Singh and Snorrason 1984	1341.0	47,319			
30 - MacDonald and Langridge-Monopolis 1984	1146.8	40,467			
31 - MacDonald and Langridge-Monopolis 1984	3762.3	132,763			
32 - Costa 1985	3469.8	122,440			
33 - Costa 1985	1119.7	39,510			
34 - Costa 1985	4203.7	148,337			
35 - Evans 1986	1266.8	44,702			
36 - Froehlich 1995	1041.2	36,741			
37 - Webby 1996	1003.5	35,409			
38 - Walder and O'Connor 1997	2853.2	100,682	95.6	55	10.75

Dam Breach Parameter Estimation
Earthen Embankment Comparative Spreadsheet

Project Data:

Dam: *Joppa - Ash Pond*
Location: *Joppa, Illinois*
Notes: *"PMP" Breach of Embankment - Breach Location 2*
Piping Failure Assumed

Inputs:

		English Units		*SI Units*	
Height of dam	h_d	23.0	feet	7.0	meters
Height of breach	h_b	23.0	feet	7.0	meters
Height/depth of water during breach	h_w	22.5	feet	6.9	meters
Storage	S	1077.0	ac-feet	1328459.9	m^3
Volume of water at breach	V_w	1077.0	ac-feet	1328459.9	m^3
Width of dam at base	W_{base}	100.0	feet	30.5	meters
Width of dam at crest	W_{crest}	30.0	feet	9.1	meters
Estimated breach side slope	Z	1.0		1.0	
Baseflow	Q_{base}	0.0	ft^3/s	0.00	m^3/s
Type of Failure		Piping			
Dam has core wall?		No			
Erosion resistant embankment?		No			

Data Convention:
- User Input Data
- Default calculation, user can change
- Calculated value.
- Adj. value

Froelich '95 Calculated Values:		**Froelich '95 Calculated Values:**				**Average Calculated Values:**			
Breach width	B_{AVG}	78.0	feet	23.8	meters	84.4	feet	25.7	meters
Breach bottom width	B_W	57.3	feet	17.5	meters	63.4	feet	19.3	meters
Breach formation time	t_f	0.77	hours	0.77	hours	0.49	hours	0.49	hours
Peak discharge	Q_p	14,946	ft^3/s	423.3	m^3/s	43,542	ft^3/s	1233.0	m^3/s
Breach side slope	Z	0.90		0.90		0.91		0.91	
Volume of embankment eroded	V_{er}	116684.3	ft^3	3304.3	m^3	126,276	ft^3	3,576	m^3
Volume of water discharged	V_o,V_{out}	1077.00	ac-feet	1328459.9	m^3	1077.0	ac-feet	1,328,460	m^3

Estimates of Breach Width & Dimensions

Source Equation (See Attached Equation Reference)	**B** (m)	**B** (ft)	**Z**	**V_{er}** (m^3)	**K_o**	$\overline{W}$ (m)	K_c	**C_b**
1 - Johnson and Illes 1976	12.3	40.3						
2 - Singh and Snorrason 1982, 1984	24.5	80.5						
3 - MacDonald and Langridge-Monopolis 1984	42.2	138.5		5869.7				
4 - MacDonald and Langridge-Monopolis 1984			0.500					
5 - FERC 1987	21.0	69.0						
6 - FERC 1987			0.625					
7 - Froehlich 1987	26.0	85.2			1.0			
8 - Froehlich 1987			1.547			19.8	1.0	
9 - USBR 1988	20.6	67.5						
10 - Von Thun and Gillette 1990			1.000					
11 - Von Thun and Gillette 1990	35.4	116.3						18.3
12 - Froehlich 1995	23.8	78.0			1.0			
13 - Froehlich 1995			0.900					

Dam Breach Parameter Estimation
Earthen Embankment Comparative Spreadsheet

Project Data:

Dam: *Joppa - Ash Pond*
Location: *Joppa, Illinois*
Notes: *"PMP" Breach of Embankment - Breach Location 2*
Piping Failure Assumed

Inputs:

		English Units		*SI Units*	
Height of dam	h_d	23.0	feet	7.0	meters
Height of breach	h_b	23.0	feet	7.0	meters
Height/depth of water during breach	h_w	22.5	feet	6.9	meters
Storage	S	1077.0	ac-feet	1328459.9	m^3
Volume of water at breach	V_w	1077.0	ac-feet	1328459.9	m^3
Width of dam at base	W_{base}	100.0	feet	30.5	meters
Width of dam at crest	W_{crest}	30.0	feet	9.1	meters
Estimated breach side slope	Z	1.0		1.0	
Baseflow	Q_{base}	0.0	ft^3/s	0.00	m^3/s
Type of Failure		Piping			
Dam has core wall?		No			
Erosion resistant embankment?		No			

Data Convention:
- User Input Data
- Default calculation, user can change
- Calculated value.
- Adj. value

Froelich '95 Calculated Values:		**Froelich '95 Calculated Values:**				**Average Calculated Values:**			
Breach width	B_{AVG}	78.0	feet	23.8	meters	84.4	feet	25.7	meters
Breach bottom width	B_W	57.3	feet	17.5	meters	63.4	feet	19.3	meters
Breach formation time	t_f	0.77	hours	0.77	hours	0.49	hours	0.49	hours
Peak discharge	Q_p	14,946	ft^3/s	423.3	m^3/s	43,542	ft^3/s	1233.0	m^3/s
Breach side slope	Z	0.90		0.90		0.91		0.91	
Volume of embankment eroded	V_{er}	116684.3	ft^3	3304.3	m^3	126,276	ft^3	3,576	m^3
Volume of water discharged	V_o,V_{out}	1077.00	ac-feet	1328459.9	m^3	1077.0	ac-feet	1,328,460	m^3

Estimates of Failure Time

Source Equation (See Attached Equation Reference)	t_f (hours)
14 - Singh and Snorrason 1982, 1984	0.625
15 - MacDonald and Langridge-Monopolis 1984	0.421
16 - FERC 1987	0.550
17 - Froehlich 1987	0.899
18 - USBR 1988	0.262
19 - Von Thun and Gillette 1990	
20 - Von Thun and Gillette 1990	
21 - Von Thun and Gillette 1990	0.103
22 - Von Thun and Gillette 1990	0.269
23 - Froehlich 1995	0.774

Dam Breach Parameter Estimation
Earthen Embankment Comparative Spreadsheet

Project Data:

Dam: *Joppa - Ash Pond*
Location: *Joppa, Illinois*
Notes: *"PMP" Breach of Embankment - Breach Location 2*
Piping Failure Assumed

Inputs:

		English Units		*SI Units*	
Height of dam	h_d	23.0	feet	7.0	meters
Height of breach	h_b	23.0	feet	7.0	meters
Height/depth of water during breach	h_w	22.5	feet	6.9	meters
Storage	S	1077.0	ac-feet	1328459.9	m^3
Volume of water at breach	V_w	1077.0	ac-feet	1328459.9	m^3
Width of dam at base	W_{base}	100.0	feet	30.5	meters
Width of dam at crest	W_{crest}	30.0	feet	9.1	meters
Estimated breach side slope	Z	1.0		1.0	
Baseflow	Q_{base}	0.0	ft^3/s	0.00	m^3/s
Type of Failure		Piping			
Dam has core wall?		No			
Erosion resistant embankment?		No			

Data Convention:
- User Input Data
- Default calculation, user can change
- Calculated value.
- Adj. value

Froelich '95 Calculated Values:		**Froelich '95 Calculated Values:**				**Average Calculated Values:**			
Breach width	B_{AVG}	78.0	feet	23.8	meters	84.4	feet	25.7	meters
Breach bottom width	B_W	57.3	feet	17.5	meters	63.4	feet	19.3	meters
Breach formation time	t_f	0.77	hours	0.77	hours	0.49	hours	0.49	hours
Peak discharge	Q_p	14,946	ft^3/s	423.3	m^3/s	43,542	ft^3/s	1233.0	m^3/s
Breach side slope	Z	0.90		0.90		0.91		0.91	
Volume of embankment eroded	V_{er}	116684.3	ft^3	3304.3	m^3	126,276	ft^3	3,576	m^3
Volume of water discharged	V_o,V_{out}	1077.00	ac-feet	1328459.9	m^3	1077.0	ac-feet	1,328,460	m^3

Estimates of Peak Discharge

Source Equation (See Attached Equation Reference)	**Q_p (m^3/s)**	**Q_p (ft^3/s)**	η	**k**	**d**
24 - Kirkpatrick 1977	173.9	6,137			
25 - SCS 1981	585.2	20,649			
26 - Hagen 1982	1648.1	58,159			
27 - USBR 1982	673.3	23,759			
28 - Singh and Snorrason 1984	531.8	18,767			
29 - Singh and Snorrason 1984	1341.0	47,319			
30 - MacDonald and Langridge-Monopolis 1984	850.3	30,006			
31 - MacDonald and Langridge-Monopolis 1984	2791.8	98,515			
32 - Costa 1985	3469.8	122,440			
33 - Costa 1985	829.3	29,265			
34 - Costa 1985	3069.5	108,314			
35 - Evans 1986	1266.8	44,702			
36 - Froehlich 1995	423.3	14,936			
37 - Webby 1996	363.2	12,816			
38 - Walder and O'Connor 1997	478.0	16,867	1166.1	55	5.26

Dam Breach Parameter Estimation
Earthen Embankment Comparative Spreadsheet

Project Data:

Dam: *Joppa - Ash Pond*
Location: *Joppa, Illinois*
Notes: *"PMP" Breach of Embankment - Breach location 3*
Piping Failure Assumed

Inputs:

		English Units		SI Units	
Height of dam	h_d	20.0	feet	6.1	meters
Height of breach	h_b	20.0	feet	6.1	meters
Height/depth of water during breach	h_w	19.5	feet	5.9	meters
Storage	S	1077.0	ac-feet	1328459.9	m^3
Volume of water at breach	V_w	1077.0	ac-feet	1328459.9	m^3
Width of dam at base	W_{base}	100.0	feet	30.5	meters
Width of dam at crest	W_{crest}	30.0	feet	9.1	meters
Estimated breach side slope	Z	1.0		1.0	
Baseflow	Q_{base}	0.0	ft^3/s	0.00	m^3/s
Type of Failure		Piping			
Dam has core wall?		No			
Erosion resistant embankment?		No			

Data Convention:
- User Input Data
- Default calculation, user can change.
- Calculated value.
- Adj. value

Froelich '95 Calculated Values:		**Froelich '95 Calculated Values:**				**Average Calculated Values:**			
Breach width	B_{AVG}	75.9	feet	23.2	meters	79.2	feet	24.1	meters
Breach bottom width	B_W	57.9	feet	17.7	meters	60.2	feet	18.4	meters
Breach formation time	t_f	0.88	hours	0.88	hours	0.51	hours	0.51	hours
Peak discharge	Q_p	12,516	ft^3/s	354.4	m^3/s	40,500	ft^3/s	1146.9	m^3/s
Breach side slope	Z	0.90		0.90		0.95		0.95	
Volume of embankment eroded	V_{er}	98805.7	ft^3	2798.0	m^3	102,969	ft^3	2,916	m^3
Volume of water discharged	V_o,V_{out}	1077.00	ac-feet	1328459.9	m^3	1077.0	ac-feet	1,328,460	m^3

Estimates of Breach Width & Dimensions

Source Equation (See Attached Equation Reference)	**B** (m)	**B** (ft)	**Z**	**V_{er}** (m^3)	**K_o**	$\overline{W}$ (m)	K_c	**C_b**
1 - Johnson and Illes 1976	10.7	35.0						
2 - Singh and Snorrason 1982, 1984	21.3	70.0						
3 - MacDonald and Langridge-Monopolis 1984	43.5	142.7		5258.1				
4 - MacDonald and Langridge-Monopolis 1984			0.500					
5 - FERC 1987	18.3	60.0						
6 - FERC 1987			0.625					
7 - Froehlich 1987	25.1	82.2			1.0			
8 - Froehlich 1987			1.704			19.8	1.0	
9 - USBR 1988	17.8	58.5						
10 - Von Thun and Gillette 1990			1.000					
11 - Von Thun and Gillette 1990	33.2	108.8						18.3
12 - Froehlich 1995	23.2	75.9			1.0			
13 - Froehlich 1995			0.900					

Dam Breach Parameter Estimation
Earthen Embankment Comparative Spreadsheet

Project Data:

Dam: *Joppa - Ash Pond*
Location: *Joppa, Illinois*
Notes: *"PMP" Breach of Embankment - Breach location 3*
Piping Failure Assumed

Inputs:

		English Units		*SI Units*	
Height of dam	h_d	20.0	feet	6.1	meters
Height of breach	h_b	20.0	feet	6.1	meters
Height/depth of water during breach	h_w	19.5	feet	5.9	meters
Storage	S	1077.0	ac-feet	1328459.9	m^3
Volume of water at breach	V_w	1077.0	ac-feet	1328459.9	m^3
Width of dam at base	W_{base}	100.0	feet	30.5	meters
Width of dam at crest	W_{crest}	30.0	feet	9.1	meters
Estimated breach side slope	Z	1.0		1.0	
Baseflow	Q_{base}	0.0	ft^3/s	0.00	m^3/s
Type of Failure		Piping			
Dam has core wall?		No			
Erosion resistant embankment?		No			

Data Convention:
- User Input Data
- Default calculation, user can change.
- Calculated value.
- Adj. value

Froelich '95 Calculated Values:		**Froelich '95 Calculated Values:**				**Average Calculated Values:**			
Breach width	B_{AVG}	75.9	feet	23.2	meters	79.2	feet	24.1	meters
Breach bottom width	B_W	57.9	feet	17.7	meters	60.2	feet	18.4	meters
Breach formation time	t_f	0.88	hours	0.88	hours	0.51	hours	0.51	hours
Peak discharge	Q_p	12,516	ft^3/s	354.4	m^3/s	40,500	ft^3/s	1146.9	m^3/s
Breach side slope	Z	0.90		0.90		0.95		0.95	
Volume of embankment eroded	V_{er}	98805.7	ft^3	2798.0	m^3	102,969	ft^3	2,916	m^3
Volume of water discharged	V_o,V_{out}	1077.00	ac-feet	1328459.9	m^3	1077.0	ac-feet	1,328,460	m^3

Estimates of Failure Time

Source Equation (See Attached Equation Reference)	t_f (hours)
14 - Singh and Snorrason 1982, 1984	0.625
15 - MacDonald and Langridge-Monopolis 1984	0.405
16 - FERC 1987	0.550
17 - Froehlich 1987	1.021
18 - USBR 1988	0.255
19 - Von Thun and Gillette 1990	
20 - Von Thun and Gillette 1990	
21 - Von Thun and Gillette 1990	0.089
22 - Von Thun and Gillette 1990	0.273
23 - Froehlich 1995	0.878

Dam Breach Parameter Estimation
Earthen Embankment Comparative Spreadsheet

Project Data:

Dam: *Joppa - Ash Pond*
Location: *Joppa, Illinois*
Notes: *"PMP" Breach of Embankment - Breach location 3*
Piping Failure Assumed

Inputs:

		English Units		*SI Units*	
Height of dam	h_d	20.0	feet	6.1	meters
Height of breach	h_b	20.0	feet	6.1	meters
Height/depth of water during breach	h_w	19.5	feet	5.9	meters
Storage	S	1077.0	ac-feet	1328459.9	m^3
Volume of water at breach	V_w	1077.0	ac-feet	1328459.9	m^3
Width of dam at base	W_{base}	100.0	feet	30.5	meters
Width of dam at crest	W_{crest}	30.0	feet	9.1	meters
Estimated breach side slope	Z	1.0		1.0	
Baseflow	Q_{base}	0.0	ft^3/s	0.00	m^3/s
Type of Failure		Piping			
Dam has core wall?		No			
Erosion resistant embankment?		No			

Data Convention:
- User Input Data
- Default calculation, user can change.
- Calculated value.
- Adj. value

Froelich '95 Calculated Values:		**Froelich '95 Calculated Values:**				**Average Calculated Values:**			
Breach width	B_{AVG}	75.9	feet	23.2	meters	79.2	feet	24.1	meters
Breach bottom width	B_W	57.9	feet	17.7	meters	60.2	feet	18.4	meters
Breach formation time	t_f	0.88	hours	0.88	hours	0.51	hours	0.51	hours
Peak discharge	Q_p	12,516	ft^3/s	354.4	m^3/s	40,500	ft^3/s	1146.9	m^3/s
Breach side slope	Z	0.90		0.90		0.95		0.95	
Volume of embankment eroded	V_{er}	98805.7	ft^3	2798.0	m^3	102,969	ft^3	2,916	m^3
Volume of water discharged	V_o,V_{out}	1077.00	ac-feet	1328459.9	m^3	1077.0	ac-feet	1,328,460	m^3

Estimates of Peak Discharge

Source Equation (See Attached Equation Reference)	**Q_p (m^3/s)**	**Q_p (ft^3/s)**	η	**k**	**d**
24 - Kirkpatrick 1977	123.6	4,361			
25 - SCS 1981	449.1	15,846			
26 - Hagen 1982	1536.9	54,233			
27 - USBR 1982	516.7	18,233			
28 - Singh and Snorrason 1984	408.4	14,410			
29 - Singh and Snorrason 1984	1341.0	47,319			
30 - MacDonald and Langridge-Monopolis 1984	801.6	28,288			
31 - MacDonald and Langridge-Monopolis 1984	2632.3	92,888			
32 - Costa 1985	3469.8	122,440			
33 - Costa 1985	782.1	27,597			
34 - Costa 1985	2886.4	101,854			
35 - Evans 1986	1266.8	44,702			
36 - Froehlich 1995	354.4	12,507			
37 - Webby 1996	297.2	10,489			
38 - Walder and O'Connor 1997	337.0	11,893	1901.9	55	4.57

Dam Breach Parameter Estimation
Earthen Embankment Comparative Spreadsheet

Project Data:

Dam: *Joppa - Ash Pond*
Location: *Joppa, Illinois*
Notes: *"PMP" Breach of Embankment - Breach Location 4*
Piping Failure Assumed

Inputs:

		English Units		*SI Units*	
Height of dam	h_d	18.0	feet	5.5	meters
Height of breach	h_b	18.0	feet	5.5	meters
Height/depth of water during breach	h_w	17.5	feet	5.3	meters
Storage	S	1077.0	ac-feet	1328459.9	m^3
Volume of water at breach	V_w	1077.0	ac-feet	1328459.9	m^3
Width of dam at base	W_{base}	100.0	feet	30.5	meters
Width of dam at crest	W_{crest}	30.0	feet	9.1	meters
Estimated breach side slope	Z	1.0		1.0	
Baseflow	Q_{base}	0.0	ft^3/s	0.00	m^3/s
Type of Failure		Piping			
Dam has core wall?		No			
Erosion resistant embankment?		No			

Data Convention:
- User Input Data
- Default calculation, user can
- Calculated value.
- Adj. value

Froelich '95 Calculated Values:		**Froelich '95 Calculated Values:**				**Average Calculated Values:**			
Breach width	B_{AVG}	74.4	feet	22.7	meters	75.7	feet	23.1	meters
Breach bottom width	B_W	58.2	feet	17.8	meters	58.2	feet	17.7	meters
Breach formation time	t_f	0.97	hours	0.97	hours	0.53	hours	0.53	hours
Peak discharge	Q_p	10,945	ft^3/s	309.9	m^3/s	38,536	ft^3/s	1091.3	m^3/s
Breach side slope	Z	0.90		0.90		0.97		0.97	
Volume of embankment eroded	V_{er}	87162.6	ft^3	2468.3	m^3	88,582	ft^3	2,508	m^3
Volume of water discharged	V_o,V_{out}	1077.00	ac-feet	1328459.9	m^3	1077.0	ac-feet	1,328,460	m^3

Estimates of Breach Width & Dimensions

Source Equation (See Attached Equation Reference)	**B** (m)	**B** (ft)	**Z**	**V_{er}** (m^3)	**K_o**	$\overline{W}$ (m)	K_c	**C_b**
1 - Johnson and Illes 1976	9.6	31.5						
2 - Singh and Snorrason 1982, 1984	19.2	63.0						
3 - MacDonald and Langridge-Monopolis 1984	44.5	145.9		4838.2				
4 - MacDonald and Langridge-Monopolis 1984			0.500					
5 - FERC 1987	16.5	54.0						
6 - FERC 1987			0.625					
7 - Froehlich 1987	24.4	80.1			1.0			
8 - Froehlich 1987			1.832			19.8	1.0	
9 - USBR 1988	16.0	52.5						
10 - Von Thun and Gillette 1990			1.000					
11 - Von Thun and Gillette 1990	31.6	103.8						18.3
12 - Froehlich 1995	22.7	74.4			1.0			
13 - Froehlich 1995			0.900					

Dam Breach Parameter Estimation
Earthen Embankment Comparative Spreadsheet

Project Data:

Dam: *Joppa - Ash Pond*
Location: *Joppa, Illinois*
Notes: *"PMP" Breach of Embankment - Breach Location 4*
Piping Failure Assumed

Inputs:

		English Units		*SI Units*	
Height of dam	h_d	18.0	feet	5.5	meters
Height of breach	h_b	18.0	feet	5.5	meters
Height/depth of water during breach	h_w	17.5	feet	5.3	meters
Storage	S	1077.0	ac-feet	1328459.9	m^3
Volume of water at breach	V_w	1077.0	ac-feet	1328459.9	m^3
Width of dam at base	W_{base}	100.0	feet	30.5	meters
Width of dam at crest	W_{crest}	30.0	feet	9.1	meters
Estimated breach side slope	Z	1.0		1.0	
Baseflow	Q_{base}	0.0	ft^3/s	0.00	m^3/s
Type of Failure		Piping			
Dam has core wall?		No			
Erosion resistant embankment?		No			

Data Convention:
- User Input Data
- Default calculation, user can
- Calculated value.
- Adj. value

Froelich '95 Calculated Values:		**Froelich '95 Calculated Values:**				**Average Calculated Values:**			
Breach width	B_{AVG}	74.4	feet	22.7	meters	75.7	feet	23.1	meters
Breach bottom width	B_W	58.2	feet	17.8	meters	58.2	feet	17.7	meters
Breach formation time	t_f	0.97	hours	0.97	hours	0.53	hours	0.53	hours
Peak discharge	Q_p	10,945	ft^3/s	309.9	m^3/s	38,536	ft^3/s	1091.3	m^3/s
Breach side slope	Z	0.90		0.90		0.97		0.97	
Volume of embankment eroded	V_{er}	87162.6	ft^3	2468.3	m^3	88,582	ft^3	2,508	m^3
Volume of water discharged	V_o,V_{out}	1077.00	ac-feet	1328459.9	m^3	1077.0	ac-feet	1,328,460	m^3

Estimates of Failure Time

Source Equation (See Attached Equation Reference)	t_f (hours)
14 - Singh and Snorrason 1982, 1984	0.625
15 - MacDonald and Langridge-Monopolis 1984	0.393
16 - FERC 1987	0.550
17 - Froehlich 1987	1.124
18 - USBR 1988	0.250
19 - Von Thun and Gillette 1990	
20 - Von Thun and Gillette 1990	
21 - Von Thun and Gillette 1990	0.080
22 - Von Thun and Gillette 1990	0.276
23 - Froehlich 1995	0.965

Dam Breach Parameter Estimation
Earthen Embankment Comparative Spreadsheet

Project Data:

Dam: *Joppa - Ash Pond*
Location: *Joppa, Illinois*
Notes: *"PMP" Breach of Embankment - Breach Location 4*
Piping Failure Assumed

Inputs:

		English Units		*SI Units*	
Height of dam	h_d	18.0	feet	5.5	meters
Height of breach	h_b	18.0	feet	5.5	meters
Height/depth of water during breach	h_w	17.5	feet	5.3	meters
Storage	S	1077.0	ac-feet	1328459.9	m^3
Volume of water at breach	V_w	1077.0	ac-feet	1328459.9	m^3
Width of dam at base	W_{base}	100.0	feet	30.5	meters
Width of dam at crest	W_{crest}	30.0	feet	9.1	meters
Estimated breach side slope	Z	1.0		1.0	
Baseflow	Q_{base}	0.0	ft^3/s	0.00	m^3/s
Type of Failure		Piping			
Dam has core wall?		No			
Erosion resistant embankment?		No			

Data Convention:
- User Input Data
- Default calculation, user can
- Calculated value.
- Adj. value

Froelich '95 Calculated Values:		**Froelich '95 Calculated Values:**				**Average Calculated Values:**			
Breach width	B_{AVG}	74.4	feet	22.7	meters	75.7	feet	23.1	meters
Breach bottom width	B_W	58.2	feet	17.8	meters	58.2	feet	17.7	meters
Breach formation time	t_f	0.97	hours	0.97	hours	0.53	hours	0.53	hours
Peak discharge	Q_p	10,945	ft^3/s	309.9	m^3/s	38,536	ft^3/s	1091.3	m^3/s
Breach side slope	Z	0.90		0.90		0.97		0.97	
Volume of embankment eroded	V_{er}	87162.6	ft^3	2468.3	m^3	88,582	ft^3	2,508	m^3
Volume of water discharged	V_o,V_{out}	1077.00	ac-feet	1328459.9	m^3	1077.0	ac-feet	1,328,460	m^3

Estimates of Peak Discharge

Source Equation (See Attached Equation Reference)	**Q_p (m^3/s)**	**Q_p (ft^3/s)**	η	**k**	**d**
24 - Kirkpatrick 1977	95.6	3,373			
25 - SCS 1981	367.6	12,971			
26 - Hagen 1982	1458.0	51,450			
27 - USBR 1982	422.9	14,925			
28 - Singh and Snorrason 1984	334.6	11,808			
29 - Singh and Snorrason 1984	1341.0	47,319			
30 - MacDonald and Langridge-Monopolis 1984	766.7	27,054			
31 - MacDonald and Langridge-Monopolis 1984	2517.8	88,847			
32 - Costa 1985	3469.8	122,440			
33 - Costa 1985	748.2	26,402			
34 - Costa 1985	2755.7	97,240			
35 - Evans 1986	1266.8	44,702			
36 - Froehlich 1995	309.9	10,937			
37 - Webby 1996	255.5	9,014			
38 - Walder and O'Connor 1997	259.0	9,139	2750.0	55	4.12

Dam Breach Parameter Estimation
Earthen Embankment Comparative Spreadsheet

Project Data:

Dam: *Joppa - Ash Pond*
Location: *Joppa, Illinois*
Notes: *"PMP" Breach of Embankment - Breach Location 5*
Piping Failure Assumed

Inputs:

		English Units		*SI Units*	
Height of dam	h_d	25.0	feet	7.6	meters
Height of breach	h_b	25.0	feet	7.6	meters
Height/depth of water during breach	h_w	24.5	feet	7.5	meters
Storage	S	1077.0	ac-feet	1328459.9	m^3
Volume of water at breach	V_w	1077.0	ac-feet	1328459.9	m^3
Width of dam at base	W_{base}	100.0	feet	30.5	meters
Width of dam at crest	W_{crest}	30.0	feet	9.1	meters
Estimated breach side slope	Z	1.0		1.0	
Baseflow	Q_{base}	0.0	ft^3/s	0.00	m^3/s
Type of Failure		Piping			
Dam has core wall?		No			
Erosion resistant embankment?		No			

Data Convention:
- User Input Data
- Default calculation, user can change
- Calculated value.
- Adj. value

Froelich '95 Calculated Values:		**Froelich '95 Calculated Values:**				**Average Calculated Values:**			
Breach width	B_{AVG}	79.2	feet	24.2	meters	87.9	feet	26.8	meters
Breach bottom width	B_W	56.7	feet	17.3	meters	65.5	feet	20.0	meters
Breach formation time	t_f	0.72	hours	0.72	hours	0.48	hours	0.48	hours
Peak discharge	Q_p	16,611	ft^3/s	470.4	m^3/s	45,644	ft^3/s	1292.6	m^3/s
Breach side slope	Z	0.90		0.90		0.90		0.90	
Volume of embankment eroded	V_{er}	128856.0	ft^3	3648.9	m^3	142,965	ft^3	4,048	m^3
Volume of water discharged	V_o,V_{out}	1077.00	ac-feet	1328459.9	m^3	1077.0	ac-feet	1,328,460	m^3

Estimates of Breach Width & Dimensions

Source Equation (See Attached Equation Reference)	**B** (m)	**B** (ft)	**Z**	**V_{er}** (m^3)	**K_o**	$\overline{W}$ (m)	K_c	**C_b**
1 - Johnson and Illes 1976	13.3	43.8						
2 - Singh and Snorrason 1982, 1984	26.7	87.5						
3 - MacDonald and Langridge-Monopolis 1984	41.5	136.1		6267.0				
4 - MacDonald and Langridge-Monopolis 1984			0.500					
5 - FERC 1987	22.9	75.0						
6 - FERC 1987			0.625					
7 - Froehlich 1987	26.5	87.0			1.0			
8 - Froehlich 1987			1.460			19.8	1.0	
9 - USBR 1988	22.4	73.5						
10 - Von Thun and Gillette 1990			1.000					
11 - Von Thun and Gillette 1990	37.0	121.3						18.3
12 - Froehlich 1995	24.2	79.2			1.0			
13 - Froehlich 1995			0.900					

Dam Breach Parameter Estimation
Earthen Embankment Comparative Spreadsheet

Project Data:

Dam: *Joppa - Ash Pond*
Location: *Joppa, Illinois*
Notes: *"PMP" Breach of Embankment - Breach Location 5*
Piping Failure Assumed

Inputs:

		English Units		*SI Units*	
Height of dam	h_d	25.0	feet	7.6	meters
Height of breach	h_b	25.0	feet	7.6	meters
Height/depth of water during breach	h_w	24.5	feet	7.5	meters
Storage	S	1077.0	ac-feet	1328459.9	m^3
Volume of water at breach	V_w	1077.0	ac-feet	1328459.9	m^3
Width of dam at base	W_{base}	100.0	feet	30.5	meters
Width of dam at crest	W_{crest}	30.0	feet	9.1	meters
Estimated breach side slope	Z	1.0		1.0	
Baseflow	Q_{base}	0.0	ft^3/s	0.00	m^3/s
Type of Failure		Piping			
Dam has core wall?		No			
Erosion resistant embankment?		No			

Data Convention:
- User Input Data
- Default calculation, user can change
- Calculated value.
- Adj. value

Froelich '95 Calculated Values:		**Froelich '95 Calculated Values:**				**Average Calculated Values:**			
Breach width	B_{AVG}	79.2	feet	24.2	meters	87.9	feet	26.8	meters
Breach bottom width	B_W	56.7	feet	17.3	meters	65.5	feet	20.0	meters
Breach formation time	t_f	0.72	hours	0.72	hours	0.48	hours	0.48	hours
Peak discharge	Q_p	16,611	ft^3/s	470.4	m^3/s	45,644	ft^3/s	1292.6	m^3/s
Breach side slope	Z	0.90		0.90		0.90		0.90	
Volume of embankment eroded	V_{er}	128856.0	ft^3	3648.9	m^3	142,965	ft^3	4,048	m^3
Volume of water discharged	V_o,V_{out}	1077.00	ac-feet	1328459.9	m^3	1077.0	ac-feet	1,328,460	m^3

Estimates of Failure Time

Source Equation (See Attached Equation Reference)	t_f (hours)
14 - Singh and Snorrason 1982, 1984	0.625
15 - MacDonald and Langridge-Monopolis 1984	0.432
16 - FERC 1987	0.550
17 - Froehlich 1987	0.834
18 - USBR 1988	0.266
19 - Von Thun and Gillette 1990	
20 - Von Thun and Gillette 1990	
21 - Von Thun and Gillette 1990	0.112
22 - Von Thun and Gillette 1990	0.266
23 - Froehlich 1995	0.718

Dam Breach Parameter Estimation
Earthen Embankment Comparative Spreadsheet

Project Data:

Dam: *Joppa - Ash Pond*
Location: *Joppa, Illinois*
Notes: *"PMP" Breach of Embankment - Breach Location 5*
Piping Failure Assumed

Inputs:

		English Units		*SI Units*	
Height of dam	h_d	25.0	feet	7.6	meters
Height of breach	h_b	25.0	feet	7.6	meters
Height/depth of water during breach	h_w	24.5	feet	7.5	meters
Storage	S	1077.0	ac-feet	1328459.9	m^3
Volume of water at breach	V_w	1077.0	ac-feet	1328459.9	m^3
Width of dam at base	W_{base}	100.0	feet	30.5	meters
Width of dam at crest	W_{crest}	30.0	feet	9.1	meters
Estimated breach side slope	Z	1.0		1.0	
Baseflow	Q_{base}	0.0	ft^3/s	0.00	m^3/s
Type of Failure		Piping			
Dam has core wall?		No			
Erosion resistant embankment?		No			

Data Convention:
- User Input Data
- Default calculation, user can change
- Calculated value.
- Adj. value

Froelich '95 Calculated Values:		**Froelich '95 Calculated Values:**				**Average Calculated Values:**			
Breach width	B_{AVG}	79.2	feet	24.2	meters	87.9	feet	26.8	meters
Breach bottom width	B_W	56.7	feet	17.3	meters	65.5	feet	20.0	meters
Breach formation time	t_f	0.72	hours	0.72	hours	0.48	hours	0.48	hours
Peak discharge	Q_p	16,611	ft^3/s	470.4	m^3/s	45,644	ft^3/s	1292.6	m^3/s
Breach side slope	Z	0.90		0.90		0.90		0.90	
Volume of embankment eroded	V_{er}	128856.0	ft^3	3648.9	m^3	142,965	ft^3	4,048	m^3
Volume of water discharged	V_o,V_{out}	1077.00	ac-feet	1328459.9	m^3	1077.0	ac-feet	1,328,460	m^3

Estimates of Peak Discharge

Source Equation (See Attached Equation Reference)	**Q_p (m^3/s)**	**Q_p (ft^3/s)**	η	**k**	**d**
24 - Kirkpatrick 1977	213.4	7,529			
25 - SCS 1981	685.0	24,172			
26 - Hagen 1982	1718.3	60,635			
27 - USBR 1982	788.2	27,813			
28 - Singh and Snorrason 1984	622.6	21,970			
29 - Singh and Snorrason 1984	1341.0	47,319			
30 - MacDonald and Langridge-Monopolis 1984	880.7	31,077			
31 - MacDonald and Langridge-Monopolis 1984	2891.2	102,024			
32 - Costa 1985	3469.8	122,440			
33 - Costa 1985	858.9	30,309			
34 - Costa 1985	3184.2	112,362			
35 - Evans 1986	1266.8	44,702			
36 - Froehlich 1995	470.4	16,599			
37 - Webby 1996	409.2	14,438			
38 - Walder and O'Connor 1997	588.8	20,776	871.0	55	5.72

Dam Breach Parameter Estimation
Earthen Embankment Comparative Spreadsheet

Project Data:

Dam: *Joppa - Ash Pond*
Location: *Joppa, Illinois*
Notes: *"PMP" Breach of Embankment - Breach Location 6*
Piping Failure Assumed

Inputs:

		English Units		*SI Units*	
Height of dam	h_d	30.0	feet	9.1	meters
Height of breach	h_b	30.0	feet	9.1	meters
Height/depth of water during breach	h_w	29.5	feet	9.0	meters
Storage	S	1077.0	ac-feet	1328459.9	m^3
Volume of water at breach	V_w	1077.0	ac-feet	1328459.9	m^3
Width of dam at base	W_{base}	100.0	feet	30.5	meters
Width of dam at crest	W_{crest}	30.0	feet	9.1	meters
Estimated breach side slope	Z	1.0		1.0	
Baseflow	Q_{base}	0.0	ft^3/s	0.00	m^3/s
Type of Failure		Piping			
Dam has core wall?		No			
Erosion resistant embankment?		No			

Data Convention:
- User Input Data
- Default calculation, user cap
- Calculated value.
- Adj. value

Froelich '95 Calculated Values:		**Froelich '95 Calculated Values:**				**Average Calculated Values:**			
Breach width	B_{AVG}	82.0	feet	25.0	meters	96.7	feet	29.5	meters
Breach bottom width	B_W	55.0	feet	16.8	meters	70.9	feet	21.6	meters
Breach formation time	t_f	0.61	hours	0.61	hours	0.45	hours	0.45	hours
Peak discharge	Q_p	20,913	ft^3/s	592.2	m^3/s	51,204	ft^3/s	1450.0	m^3/s
Breach side slope	Z	0.90		0.90		0.86		0.86	
Volume of embankment eroded	V_{er}	160077.6	ft^3	4533.1	m^3	188,713	ft^3	5,344	m^3
Volume of water discharged	V_o,V_{out}	1077.00	ac-feet	1328459.9	m^3	1077.0	ac-feet	1,328,460	m^3

Estimates of Breach Width & Dimensions

Source Equation (See Attached Equation Reference)	**B** (m)	**B** (ft)	**Z**	**V_{er}** (m^3)	**K_o**	$\overline{W}$ (m)	K_c	**C_b**
1 - Johnson and Illes 1976	16.0	52.5						
2 - Singh and Snorrason 1982, 1984	32.0	105.0						
3 - MacDonald and Langridge-Monopolis 1984	39.9	130.8		7229.1				
4 - MacDonald and Langridge-Monopolis 1984			0.500					
5 - FERC 1987	27.4	90.0						
6 - FERC 1987			0.625					
7 - Froehlich 1987	27.7	91.0			1.0			
8 - Froehlich 1987			1.284			19.8	1.0	
9 - USBR 1988	27.0	88.5						
10 - Von Thun and Gillette 1990			1.000					
11 - Von Thun and Gillette 1990	40.8	133.8						18.3
12 - Froehlich 1995	25.0	82.0			1.0			
13 - Froehlich 1995			0.900					

Dam Breach Parameter Estimation
Earthen Embankment Comparative Spreadsheet

Project Data:

Dam: *Joppa - Ash Pond*
Location: *Joppa, Illinois*
Notes: *"PMP" Breach of Embankment - Breach Location 6*
Piping Failure Assumed

Inputs:

		English Units		*SI Units*	
Height of dam	h_d	30.0	feet	9.1	meters
Height of breach	h_b	30.0	feet	9.1	meters
Height/depth of water during breach	h_w	29.5	feet	9.0	meters
Storage	S	1077.0	ac-feet	1328459.9	m^3
Volume of water at breach	V_w	1077.0	ac-feet	1328459.9	m^3
Width of dam at base	W_{base}	100.0	feet	30.5	meters
Width of dam at crest	W_{crest}	30.0	feet	9.1	meters
Estimated breach side slope	Z	1.0		1.0	
Baseflow	Q_{base}	0.0	ft^3/s	0.00	m^3/s
Type of Failure		Piping			
Dam has core wall?		No			
Erosion resistant embankment?		No			

Data Convention:
- User Input Data
- Default calculation, user cap
- Calculated value.
- Adj. value

Froelich '95 Calculated Values:		**Froelich '95 Calculated Values:**				**Average Calculated Values:**			
Breach width	B_{AVG}	82.0	feet	25.0	meters	96.7	feet	29.5	meters
Breach bottom width	B_W	55.0	feet	16.8	meters	70.9	feet	21.6	meters
Breach formation time	t_f	0.61	hours	0.61	hours	0.45	hours	0.45	hours
Peak discharge	Q_p	20,913	ft^3/s	592.2	m^3/s	51,204	ft^3/s	1450.0	m^3/s
Breach side slope	Z	0.90		0.90		0.86		0.86	
Volume of embankment eroded	V_{er}	160077.6	ft^3	4533.1	m^3	188,713	ft^3	5,344	m^3
Volume of water discharged	V_o,V_{out}	1077.00	ac-feet	1328459.9	m^3	1077.0	ac-feet	1,328,460	m^3

Estimates of Failure Time

Source Equation (See Attached Equation Reference)	t_f (hours)
14 - Singh and Snorrason 1982, 1984	0.625
15 - MacDonald and Langridge-Monopolis 1984	0.455
16 - FERC 1987	0.550
17 - Froehlich 1987	0.706
18 - USBR 1988	0.275
19 - Von Thun and Gillette 1990	
20 - Von Thun and Gillette 1990	
21 - Von Thun and Gillette 1990	0.135
22 - Von Thun and Gillette 1990	0.258
23 - Froehlich 1995	0.610

Dam Breach Parameter Estimation
Earthen Embankment Comparative Spreadsheet

Project Data:

Dam: *Joppa - Ash Pond*
Location: *Joppa, Illinois*
Notes: *"PMP" Breach of Embankment - Breach Location 6*
Piping Failure Assumed

Inputs:

		English Units		*SI Units*	
Height of dam	h_d	30.0	feet	9.1	meters
Height of breach	h_b	30.0	feet	9.1	meters
Height/depth of water during breach	h_w	29.5	feet	9.0	meters
Storage	S	1077.0	ac-feet	1328459.9	m^3
Volume of water at breach	V_w	1077.0	ac-feet	1328459.9	m^3
Width of dam at base	W_{base}	100.0	feet	30.5	meters
Width of dam at crest	W_{crest}	30.0	feet	9.1	meters
Estimated breach side slope	Z	1.0		1.0	
Baseflow	Q_{base}	0.0	ft^3/s	0.00	m^3/s
Type of Failure		Piping			
Dam has core wall?		No			
Erosion resistant embankment?		No			

Data Convention:
- User Input Data
- Default calculation, user cap
- Calculated value.
- Adj. value

Froelich '95 Calculated Values:		**Froelich '95 Calculated Values:**				**Average Calculated Values:**			
Breach width	B_{AVG}	82.0	feet	25.0	meters	96.7	feet	29.5	meters
Breach bottom width	B_W	55.0	feet	16.8	meters	70.9	feet	21.6	meters
Breach formation time	t_f	0.61	hours	0.61	hours	0.45	hours	0.45	hours
Peak discharge	Q_p	20,913	ft^3/s	592.2	m^3/s	51,204	ft^3/s	1450.0	m^3/s
Breach side slope	Z	0.90		0.90		0.86		0.86	
Volume of embankment eroded	V_{er}	160077.6	ft^3	4533.1	m^3	188,713	ft^3	5,344	m^3
Volume of water discharged	V_o,V_{out}	1077.00	ac-feet	1328459.9	m^3	1077.0	ac-feet	1,328,460	m^3

Estimates of Peak Discharge

Source Equation (See Attached Equation Reference)	**Q_p (m^3/s)**	**Q_p (ft^3/s)**	η	**k**	**d**
24 - Kirkpatrick 1977	333.9	11,782			
25 - SCS 1981	965.9	34,083			
26 - Hagen 1982	1882.3	66,422			
27 - USBR 1982	1111.3	39,216			
28 - Singh and Snorrason 1984	878.7	31,009			
29 - Singh and Snorrason 1984	1341.0	47,319			
30 - MacDonald and Langridge-Monopolis 1984	950.7	33,549			
31 - MacDonald and Langridge-Monopolis 1984	3120.5	110,116			
32 - Costa 1985	3469.8	122,440			
33 - Costa 1985	927.3	32,721			
34 - Costa 1985	3450.1	121,747			
35 - Evans 1986	1266.8	44,702			
36 - Froehlich 1995	592.2	20,897			
37 - Webby 1996	530.7	18,726			
38 - Walder and O'Connor 1997	928.7	32,773	460.1	55	6.86

Dam Breach Parameter Spreadsheet

Equations, Procedures, and Notes

Last Updated/By: 8-24-12 – Erman Caudill (Stantec)

Assumptions:

- Equations here were extracted from the USBR Report "Prediction of Embankment Dam Breach Parameters" and the Journal of Hydraulic Engineering article "Uncertainty of Predictions of Embankment Dam Breach Parameters" by the same author (Tony L. Wahl, USBR). Citation for that reference is included below, but recursive references have been omitted.
- All earthen embankments.
- Measurements are in SI units (meters, m^3/s, hours) unless otherwise noted. Spreadsheet is set up to do the English-SI input conversions, then convert answers back to English units.

Input Parameters, Constants, and Variables:

h_d = height of dam: input
h_b = height of breach: input, generally = h_d
h_w = height (depth) of water at failure above breach bottom: input
S = storage: input parameter
V_w = volume of water above breach invert at time of breach: input, generally = S
W = Embankment width: input
Z = breach opening side slope: input or calculated

g = acceleration of gravity = 9.8 m/s^2 =127,008,000 m/hr^2

B = average breach width: calculated (see below)
B_W = breach bottom width: calculated using B, h_b, and Z (see equation 39)
t_f = breach formation time, hours: calculated (see below)
Q_p = peak breach outflow: calculated (see below)
Z = breach opening side slope: input or calculated (see below)
V_{er} = volume of embankment material eroded: generally calculated (see Equation 40)
V_o,V_{out} = volume of water discharged: calculated = S + inflow during breach

Breach Width & Dimension Equations:

Johnson and Illes 1976

(1) $0.5h_d \leq B \leq 3h_d$

Singh and Snorrason 1982, 1984

(2) $2h_d \leq B \leq 5h_d$

MacDonald and Langridge-Monopolis 1984

(3) $V_{er} = 0.0261(V_{out}h_w)^{0.769}$

(4) $Z = 1H{:}2V$

FERC 1987

(5) $2h_d \leq B \leq 4h_d$

(6) $0.25 \leq Z \leq 1.0$

Froehlich 1987

$$\overline{B^*} = \frac{\overline{B}}{h} = 0.47K_o(S^*)^{0.25}$$

$$S^* = \frac{S}{{h_b}^3}$$

(7) $\overline{B} = 0.47 h_b K_o \left(\frac{S}{h_b{}^3}\right)^{0.25}$ Ko = 1.4 overtopping; 1.0 otherwise

$$Z = 0.75 K_c (h_w{}^*)^{1.57} \left(\overline{W^*}\right)^{0.73}$$

$$h_w{}^* = \frac{h_w}{h_b}$$

$$\left(\overline{W^*}\right) = \frac{\overline{W}}{h} = \frac{W_{crest} + W_{bottom}}{2h}$$

(8) $Z = 0.75 K_c \left(\frac{h_w}{h_b}\right)^{1.57} \left(\frac{\overline{W}}{h_b}\right)^{0.73}$ Kc = 0.6 with corewall; 1.0 without a corewall

USBR 1988

(9) $B = 3h_w$

Von Thun and Gillette 1990

(10) $Z = 1H{:}1V$

(11) $\overline{B} = 2.5 h_w + C$

$$C_b = f(\text{reservoir size}, m^3) = \begin{Bmatrix} Size & C_b \\ < 1.23x10^6 & 6.1 \\ 1.23x10^6 - 6.17x10^6 & 18.3 \\ 6.17x10^6 - 1.23x10^7 & 42.7 \\ > 1.23x10^7 & 54.9 \end{Bmatrix}$$

Froehlich 1995

(12) $\overline{B} = 0.1803 K_o V_w{}^{0.32} h_b{}^{0.19}$ Ko = 1.4 overtopping; 1.0 otherwise

(13) Z = 1.4 for overtopping, 0.9 otherwise

Failure Time Equations:

Singh and Snorrason 1982, 1984

(14) $0.25 \text{ hr} \leq t_f \leq 1.0 \text{ hr}$

MacDonald and Langridge-Monopolis 1984

(15) $t_f = 0.0179 (V_{er})^{0.364}$

FERC 1987

(16) $0.10 \text{ hr} \leq t_f \leq 1.0 \text{ hr}$

Froehlich 1987 (t_f* equation was corrected from the report)

$$S^* = \frac{S}{h_b{}^3}$$

$$t_f{}^* = 79 (S^*)^{0.47} = 79 \left(\frac{S}{h_b{}^3}\right)^{0.47}$$

$$t_f{}^* = t_f \sqrt{\frac{g}{h}}$$

(17) $t_f = \frac{79 \left(\frac{S}{h_b{}^3}\right)^{0.47}}{\sqrt{\frac{g}{h_b}}}$

USBR 1988

(18) $t_f = 0.011 B$

Von Thun and Gillette 1990

Erosion Resistant

(19) $t_f = 0.020h_w + 0.25$

(20) $t_f = \frac{\overline{B}}{4h_w}$

Highly Erodible

(21) $t_f = 0.015h_w$

(22) $t_f = \frac{\overline{B}}{4h_w+61.0}$

Froehlich 1995

(23) $t_f = 0.00254{V_w}^{0.53}{h_b}^{(-0.90)}$

Peak Flow Equations:

Kirkpatrick 1977

(24) $Q_p = 1.268(h_w + 0.3)^{2.5}$

SCS 1981

(25) $Q_p = 16.6(h_w)^{1.85}$

Hagen 1982

(26) $Q_p = 0.54(S \times h_d)^{0.5}$

USBR 1982

(27) $Q_p = 19.1(h_w)^{1.85}$

Singh and Snorrason 1984

(28) $Q_p = 13.4(h_d)^{1.89}$

(29) $Q_p = 1.776(S)^{0.47}$

MacDonald and Langridge-Monopolis 1984

(30) $Q_p = 1.154(V_w h_w)^{0.412}$

(31) $Q_p = 3.85(V_w h_w)^{0.411}$

Costa 1985

(32) $Q_p = 1.122(S)^{0.57}$

(33) $Q_p = 0.981(S \times h_d)^{0.42}$

(34) $Q_p = 2.634(S \times h_d)^{0.44}$

Evans 1986

(35) $Q_p = 0.72(V_W)^{0.53}$

Froehlich 1995

(36) $Q_p = 0.607{V_w}^{0.295}{h_w}^{1.24}$

Webby 1996

(37) $Q_p = 0.0443g^{0.5}{V_w}^{0.367}{h_w}^{1.40}$

Dam Breach Parameter Spreadsheet

Equations, Procedures, and Notes

Last Updated/By: 8-24-12 – Erman Caudill (Stantec)

Walder and O'Connor 1997

$$\eta = \frac{kV_o}{g^{0.5}d^{3.5}}$$

k = vertical erosion rate = 10 m/hr – 100 m/hr
d = 50-100% of dam height

$$(38) \qquad Q_p = \begin{Bmatrix} 1.51(g^{0.5}d^{2.5})^{0.06}\left(\frac{kV_o}{d}\right)^{0.94} & \eta < \sim 0.6 \\ 1.94g^{0.5}d^{2.5}\left(\frac{h_d}{d}\right)^{0.75} & \eta \gg 1 \end{Bmatrix}$$

Other Equations:

Breach Bottom Width

$$(39) \qquad B_W = B - h_b Z$$

Embankment Volume

$$(40) \qquad V_{er} = \left(B_w h_b + Z h_b{}^2\right)\left(\frac{W_{crest} + W_{base}}{2}\right) = (Bh_b)\left(\frac{W_{crest} + W_{base}}{2}\right)$$

$$B = \frac{V_{er}}{h_b\left(\frac{W_{crest} + W_{base}}{2}\right)}$$

References:

U.S. Department of the Interior, Bureau of Reclamation, Dam Safety Office. July 1998. "Prediction of Embankment Dam Breach Parameters, A Literature Review and Needs Assessment, DSO-98-004, Dam Safety Research Report", Tony L. Wahl, Water Resources Research Laboratory. 67 pp.

"Uncertainty of Predictions of Embankment Dam Breach Parameters", Tony L. Wahl. Journal of Hydraulic Engineering, Vol. 130, No. 5, May 1, 2004. 9 pp.

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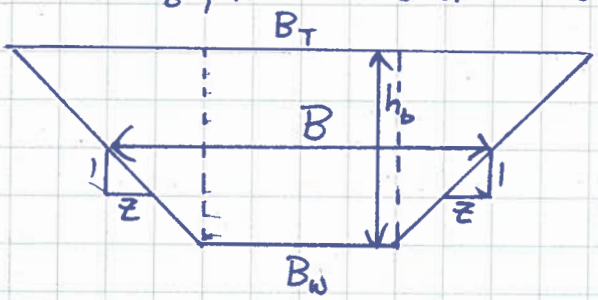
DAM BREACH EQUATIONS

DERIVATIONS NOT SHOWN

1. BREACH BOTTOM WIDTH GIVEN AVG. BREACH WIDTH B, BREACH HEIGHT H_b, AND BREACH SIDE SLOPES Z



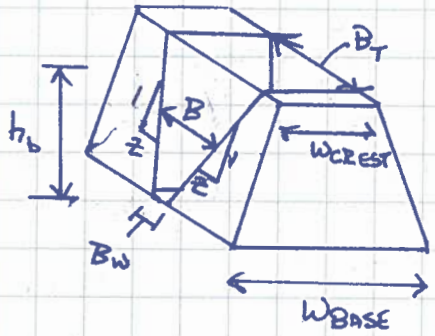
$$B = \frac{B_T + B_W}{2}$$

$$B_T = B_W + 2h_b Z$$

$$B = \frac{(B_W + 2h_b Z) + B_W}{2} = \frac{2B_W + 2h_b Z}{2} = B_W + h_b Z$$

$$B_W = B - h_b Z$$

2. VOLUME OF EMBANKMENT ERODED



AREA AT CENTER

$$A_c = B_W h_b + Z h_b^2$$

$$\forall = A_c W_{CREST} + 2\frac{A_c}{2}\frac{(W_{BASE} - W_{CREST})}{2}$$

$$= A_c W_c + \frac{A_c}{2} W_B - \frac{A_c}{2} W_c$$

$$= \frac{A_c W_c}{2} + \frac{A_c W_B}{2}$$

$$= A_c\left(\frac{W_c + W_B}{2}\right)$$

$$\forall = \left(B_W h_b + Z h_b^2\right)\left(\frac{W_c + W_B}{2}\right)$$

$$\forall = B h_b \left(\frac{W_c + W_B}{2}\right) \rightarrow B = \frac{\forall}{h_b\left(\frac{W_c + W_B}{2}\right)}$$

Designed by: Checked by: