Documentation of Initial Hazard Potential Classification Assessment

Bottom Ash Pond
Baldwin Energy Complex
Randolph County, Illinois

Prepared for:
Dynegy

October 12, 2016

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

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Executive Summary

This report documents the hazard potential classification assessment for the Bottom Ash Pond at the Baldwin Energy Complex 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 Bottom Ash Pond should be classified as a Significant Hazard Potential CCR surface impoundment.

This report contains supporting documentation for the hazard potential classification assessment. The hazard potential classification for the Bottom Ash Pond was determined by a breach analysis conducted by Stantec in September, 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 Bottom Ash Pond.

1.2. Location

Baldwin Energy Complex is located along the east bank of the Kaskaskia River and northwest of Baldwin, Illinois in Randolph County. The station is located on the north side of Illinois Route 154 (Myrtle Street), the east side of Conservation Road, and the west side of 1st Street. The station's address is 10901 Baldwin Road, Baldwin, IL 62217. A site overview figure is included in Appendix A.

2. Source Data

The following information was used to perform a hazard assessment for the Bottom Ash Pond:

[1] Dynegy Administrative Services Company (Dynegy) contracted Stantec on behalf of the Baldwin Energy Complex owner, Dynegy Midwest Generation, LLC. Thus, Dynegy is referenced in this report.

- Aerial Imagery (USDA National Aerial Imagery Program 2015)
- Topographic survey information, existing conditions (Weaver Consultants Group for Dynegy, December 2015 – 1 foot contour data and planimetrics)
- Final Report Round 10 Dam Assessment Dynegy Midwest Generation, LLC – Baldwin Energy Complex Primary Fly Ash Pond, Secondary Fly Ash Pond, Secondary Pond, Intermediate Pond, Final Pond Baldwin, Illinois, December 21, 2012
- Topographic information, pre-existing conditions (Illinois Power Company, 1981- 4 foot contours), Topographic Plan, Baldwin Power Plant Ash Storage Area
- Topographic information, Randolph County, Illinois (Illinois State Geological Survey County LiDAR Dataset, March/April 2012 – 2-foot contour interval)

3. Potential Failure Scenarios

3.1. Facility Description

The Bottom Ash Pond is located upstream of two non-CCR impoundments, the Secondary Pond and the Tertiary Pond. Pertinent geometric details for each pond were derived from the *Final Report Round 10 Dam Assessment Dynegy Midwest Generation, LLC – Baldwin Energy Complex*. Pertinent geometric details and other information are listed below.

- Bottom Ash Pond:
  - CCR Surface Impoundment – Yes
  - Dam Crest Elevation – 417.6 Feet
  - CCR Storage - Yes
- Secondary Pond:
  - CCR Surface Impoundment – No
  - Normal Pool Elevation – 396.0 Feet
  - Open Channel Spillway Elev – 400.0 Feet
  - Dam Crest Elevation – 402.0 Feet
  - Surface Area – 19.0 Acres
  - Pool Area – 18.5 Acres
  - Storage, Top of Dam – 190 Acre-Feet
  - Spillway – 50 foot wide open channel
- Tertiary Pond:

- CCR Surface Impoundment – No
- Normal Pool Elevation – 393.0 Feet
- Open Channel Spillway Elev – 394.3 Feet
- Dam Crest Elevation – 398.0 Feet
- Surface Area – 4.2 Acres
- Pool Area – 4.0 Acres
- Storage, Top of Dam – 110 Acre-Feet
- Spillway – 90 foot wide open channel

3.2. Failure Scenarios

Free water volume is defined as the storage volume available between the crest elevation and the existing surface as defined in the 2015 survey. For the purpose of this evaluation all ponds were conservatively assumed to be storing water to the crest elevation. Solids volumes used in the analysis include volume of the ponds earthen embankments and in-place waste derived by comparing the 2015 survey of the impoundment to 1981 drawings of the area.

Two breach scenarios, Scenario A and B, were developed and analyzed. Breach hydrographs were developed utilizing the US Army Corps of Engineers (USACE) Hydrologic Engineering Centers Hydrologic Modeling System (HEC-HMS) version 4.0 (Reference 2). The hydrographs were routed downstream using the two dimensional capabilities of USACE Hydrologic Engineering Center's River Analysis System (HEC-RAS) version 5.0.1 (Reference 12).

Unless otherwise noted, all elevations herein are referenced to NAVD 88.

3.2.1. Scenario A – Bottom Ash Pond Western Failure

Scenario A assumed an overtopping breach initiated along the west face of the Bottom Ash Pond. The bottom of the breach was assumed at 403.0 feet. The volume of the breach was assumed as the free water volume of the pond. Due to the consistency of the bottom ash present within the Bottom Ash Pond and the location of the ash relative to the embankment, it was assumed that negligible solids volume contributed to this breach. Discharge consisting of the free water volume would flow to the Secondary Pond.

3.2.2. Scenario B – Tertiary Pond Southwestern Failure

Scenario B assumed an overtopping breach initiated along the southwest face of the Tertiary pond as a result of a Bottom Ash Pond breach. The bottom of the breach was assumed at 376.0 feet. The volume of the breach was assumed as the free water volume of the Secondary, Tertiary, and Bottom Ash Ponds. Due to the consistency of the bottom ash present within the Bottom Ash Pond, it was assumed that negligible solids volume contributed to this breach. Discharge would flow south and southwest towards the Kaskaskia River.

3.3. Breach Hydrograph Development

Breach hydrographs were developed using HEC-HMS version 4.0. The breach function of HEC-HMS 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 engineering judgment (References 3 - 11).

Table 1 summarizes the breach parameters used for this analysis. These values are based on the assumed failure conditions, height of breach, impoundment volume above breach, and width of the embankment. B_{avg} is the average width of a breach failure and t_f is the time for the breach to fully develop.

Table 1 Summary of Estimated Dam Breach Parameters

	Scenario A	Scenario B
Range of Breach Width Estimates (feet)	13.9 – 55.0	33.9 – 80.7
Range of Failure Time Estimates (hours)	0.1 – 0.6	0.1 – 0.6
B_{avg} (feet)	40.1	63.0
t_f (hours)	0.3	0.4

There is no contributing watershed upstream of the Bottom Ash Pond; therefore runoff calculations were not performed. Each of the ponds was conservatively assumed to have water present to the crest during a breach, as could occur during an extreme storm event with a clogged or blocked principal spillway.

Stage-storage curves for the Bottom Ash Pond, Secondary Pond and Tertiary Pond were developed based on historic topographic data and 2015 existing condition survey data. The stage-storage curves were unique for each of the scenarios modeled due to the volume assumptions for each.

3.4. Hydraulic Model Development

The breach hydrographs developed from HEC-HMS were routed downstream using the two dimensional capabilities of HEC-RAS version 5.0.1.

3.4.1. Hydraulic Parameters

Pertinent hydraulic parameters used during the hydraulic analysis are summarized below.

- The two-dimensional grid size used to route the hydrographs consisted of 40 foot cells, which effectively captured terrain features while simplifying the computational mesh.
- The minimum allowable breach flow ranged from 50 to 150 cubic feet per second (cfs) depending on the breach scenario.
- The Manning's 'n' was fixed at 0.060 for all 2D grid cells assuming this represented an average 'n' across the downstream inundation area. After reviewing model results it was determined spatial variation of Manning's 'n' would not result in a different peak inundation area.
- The Full Momentum equation set was utilized to model the breach scenarios because it resulted in a more realistic inundation extent than the Diffusion Wave equations.

3.5. Breach Modeling Results

Inundation limits for the breach Scenarios A and B were evaluated to determine the potential impacts on property and structures and the potential risk to human life.

Model results have been summarized below for selected areas of impact. The modeled breach scenarios indicate potential impacts to infrastructure believed to be off property from Baldwin Energy Complex property. Discharge to the Kaskaskia River is predicted in both scenarios.

3.5.1. Breach Pathways

Scenarios A and B would progress overland to the south and west. The breaches would affect Conservation Road. No occupied structures were impacted by the breach. Conservation Road is a secondary road with intermittent traffic. In accordance with Federal guidelines, loss of life is not considered probable for scenarios where persons are only temporarily in the potential inundation area (Reference 14).

4. Hazard Classification

Areas of potential impact were identified with results discussed in Section 3.5 of this report. Based on the results of modeling a breach of the Bottom Ash Pond, it is Stantec's opinion that such an event results in no probable loss of human life, but can cause economic loss, environmental damage, disruption of lifeline facilities, or impact other concerns.

Therefore, the Bottom Ash Pond fits the definition for a Significant hazard potential CCR surface impoundment (as defined in the CCR Rule §257.53) (Reference 1).

5. Reference

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 Army Corps of Engineers, Hydrologic Engineering Center, "Hydrologic Modeling System", HEC-HMS, Version 4.0 computer program, revised December 2013

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. US Army Corps of Engineers, Hydrologic Engineering Center, "River Analysis System", HEC-RAS, Version 5.0.1 computer program, revised April 2016

13. Federal Emergency Management Association (FEMA). (2012). *Assessing the Consequences of Dam Failure*. A How-to-Guide.

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

Appendix A

Site Overview Figure

Notes

1. Coordinate System: WGS 1984 Web Mercator Auxiliary Sphere
2. Aerial Source: 2015 NAIP Imagery
3. Impoundment Boundaries Provided by Client (Dated 9/9/2015)

0 2,000 Feet

1:24,000 (At original document size of 11x17)

Stantec DYNEGY

Project Location
Latitude: 38.204579
Longitude: -89.855052
Randolph County, Illinois

175605019
Prepared by WSW on 2016-10-12
Technical Review by NS on 2016-10-12
Independent Review by MH on 2016-10-12

Client/Project
Dynegy
Baldwin Power Station
Hazard Potential Classification Assessment

Figure No.
Appendix A

Title
Site Overview Figure
Bottom Ash Pond System
Baldwin Power Station

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Appendix B

Breach Parameters

Dam Breach Parameter Estimation
Earthen Embankment Comparative Spreadsheet
Last Updated/By: 8-24-12 - Erman Caudill (Stantec)
Refer to accompanying Equation Reference document.

Stantec

Project Data (Optional):

Dam: *Baldwin Power Station*
Location: *Randolph County, Illinois*
Notes: *Scenario A - Bottom Ash Pond*

Inputs:

		English Units		SI Units	
Height of dam	h_d	14.0	feet	4.3	meters
Height of breach	h_b	14.0	feet	4.3	meters
Height/depth of water at breach	h_w	14.0	feet	4.3	meters
Storage	S	69.8	ac-feet	86084.7	m^3
Volume of water at breach	V_w	69.8	ac-feet	86084.7	m^3
Width of dam at base	W_{base}	140.0	feet	42.7	meters
Width of dam at crest	W_{crest}	40.0	feet	12.2	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		Overtopping			
Dam has core wall?		No			
Erosion resistant embankment?		No			

Data Convention:

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

Average of Calculated Values:

Breach width	B_{AVG}	40.1	feet	12.2	meters
Breach bottom width	B_W	22.1	feet	6.7	meters
Breach formation time	t_f	0.3	hours	0.31	hours
Peak discharge	Q_p	11,181	ft^3/s	316.6	m^3/s
Breach side slope	Z	1.29		1.29	
Volume of embankment eroded	V_{er}	50587.1	ft^3	1432.5	m^3
Volume of water discharged	V_o,V_{out}	69.79	ac-feet	86084.7	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	7.5	24.5						
2 - Singh and Snorrason 1982, 1984	14.9	49.0						
3 - MacDonald and Langridge-Monopolis 1984	4.2	13.9		496.9				
4 - MacDonald and Langridge-Monopolis 1984			0.500					
5 - FERC 1987	12.8	42.0						
6 - FERC 1987			0.625					
7 - Froehlich 1987	16.2	53.1			1.4			
8 - Froehlich 1987			2.917			27.4	1.0	
9 - USBR 1988	12.8	42.0						
10 - Von Thun and Gillette 1990			1.000					
11 - Von Thun and Gillette 1990	16.8	55.0						6.1
12 - Froehlich 1995	12.6	41.4			1.4			
13 - Froehlich 1995			1.400					

Dam Breach Parameter Estimation
Earthen Embankment Comparative Spreadsheet
Last Updated/By: 8-24-12 - Erman Caudill (Stantec)
Refer to accompanying Equation Reference document.

Stantec

Project Data (Optional):

Dam: *Baldwin Power Station*
Location: *Randolph County, Illinois*
Notes: *Scenario A - Bottom Ash Pond*

Inputs:

		English Units		SI Units	
Height of dam	h_d	14.0	feet	4.3	meters
Height of breach	h_b	14.0	feet	4.3	meters
Height/depth of water at breach	h_w	14.0	feet	4.3	meters
Storage	S	69.8	ac-feet	86084.7	m^3
Volume of water at breach	V_w	69.8	ac-feet	86084.7	m^3
Width of dam at base	W_{base}	140.0	feet	42.7	meters
Width of dam at crest	W_{crest}	40.0	feet	12.2	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		Overtopping			
Dam has core wall?		No			
Erosion resistant embankment?		No			

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

Average of Calculated Values:					
Breach width	B_{AVG}	40.1	feet	12.2	meters
Breach bottom width	B_W	22.1	feet	6.7	meters
Breach formation time	t_f	0.3	hours	0.31	hours
Peak discharge	Q_p	11,181	ft^3/s	316.6	m^3/s
Breach side slope	Z	1.29		1.29	
Volume of embankment eroded	V_{er}	50587.1	ft^3	1432.5	m^3
Volume of water discharged	V_o,V_{out}	69.79	ac-feet	86084.7	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	0.252
16 - FERC 1987	0.550
17 - Froehlich 1987	0.390
18 - USBR 1988	0.135
19 - Von Thun and Gillette 1990	
20 - Von Thun and Gillette 1990	
21 - Von Thun and Gillette 1990	0.064
22 - Von Thun and Gillette 1990	0.157
23 - Froehlich 1995	0.284

Dam Breach Parameter Estimation
Earthen Embankment Comparative Spreadsheet
Last Updated/By: 8-24-12 - Erman Caudill (Stantec)
Refer to accompanying Equation Reference document.

Project Data (Optional):

Dam: *Baldwin Power Station*
Location: *Randolph County, Illinois*
Notes: *Scenario A- Bottom Ash Pond*

Inputs:

		English Units		*SI Units*	
Height of dam	h_d	14.0	feet	4.3	meters
Height of breach	h_b	14.0	feet	4.3	meters
Height/depth of water at breach	h_w	14.0	feet	4.3	meters
Storage	S	69.8	ac-feet	86084.7	m^3
Volume of water at breach	V_w	69.8	ac-feet	86084.7	m^3
Width of dam at base	W_{base}	140.0	feet	42.7	meters
Width of dam at crest	W_{crest}	40.0	feet	12.2	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		Overtopping			
Dam has core wall?		No			
Erosion resistant embankment?		No			

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

Average of Calculated Values:					
Breach width	B_{AVG}	40.1	feet	12.2	meters
Breach bottom width	B_W	22.1	feet	6.7	meters
Breach formation time	t_f	0.3	hours	0.31	hours
Peak discharge	Q_p	11,181	ft^3/s	316.6	m^3/s
Breach side slope	Z	1.29		1.29	
Volume of embankment eroded	V_{er}	50587.1	ft^3	1432.5	m^3
Volume of water discharged	V_o,V_{out}	69.79	ac-feet	86084.7	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	56.6	1,996			
25 - SCS 1981	243.3	8,584			
26 - Hagen 1982	327.3	11,551			
27 - USBR 1982	279.9	9,877			
28 - Singh and Snorrason 1984	208.1	7,344			
29 - Singh and Snorrason 1984	370.6	13,076			
30 - MacDonald and Langridge-Monopolis 1984	226.5	7,992			
31 - MacDonald and Langridge-Monopolis 1984	746.0	26,325			
32 - Costa 1985	729.3	25,735			
33 - Costa 1985	213.3	7,528			
34 - Costa 1985	740.1	26,117			
35 - Evans 1986	297.1	10,482			
36 - Froehlich 1995	104.8	3,699			
37 - Webby 1996	68.5	2,416			
38 - Walder and O'Connor 1997	138.2	4,876	429.5	55	3.20

Dam Breach Parameter Estimation
Earthen Embankment Comparative Spreadsheet
Last Updated/By: 8-24-12 - Erman Caudill (Stantec)
Refer to accompanying Equation Reference document.

Project Data (Optional):

Dam: *Baldwin Power Station*
Location: *Randolph County, Illinois*
Notes: *Scenario B- Tertiary Pond*

Inputs:

		English Units		*SI Units*	
Height of dam	h_d	22.0	feet	6.7	meters
Height of breach	h_b	22.0	feet	6.7	meters
Height/depth of water at breach	h_w	22.0	feet	6.7	meters
Storage	S	236.0	ac-feet	291101.7	m^3
Volume of water at breach	V_w	236.0	ac-feet	291101.7	m^3
Width of dam at base	W_{base}	140.0	feet	42.7	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		Overtopping			
Dam has core wall?		No			
Erosion resistant embankment?		No			

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

Average of Calculated Values:

Breach width	B_{AVG}	63.0	feet	19.2	meters
Breach bottom width	B_W	38.6	feet	11.8	meters
Breach formation time	t_f	0.4	hours	0.36	hours
Peak discharge	Q_p	23,774	ft^3/s	673.2	m^3/s
Breach side slope	Z	1.11		1.11	
Volume of embankment eroded	V_{er}	117819.0	ft^3	3336.4	m^3
Volume of water discharged	V_o,V_{out}	236.00	ac-feet	291101.7	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	11.7	38.5						
2 - Singh and Snorrason 1982, 1984	23.5	77.0						
3 - MacDonald and Langridge-Monopolis 1984	10.3	33.9		1795.2				
4 - MacDonald and Langridge-Monopolis 1984			0.500					
5 - FERC 1987	20.1	66.0						
6 - FERC 1987			0.625					
7 - Froehlich 1987	24.6	80.7			1.4			
8 - Froehlich 1987			2.012			25.9	1.0	
9 - USBR 1988	20.1	66.0						
10 - Von Thun and Gillette 1990			1.000					
11 - Von Thun and Gillette 1990	22.9	75.0						6.1
12 - Froehlich 1995	20.3	66.6			1.4			
13 - Froehlich 1995			1.400					

Dam Breach Parameter Estimation
Earthen Embankment Comparative Spreadsheet
Last Updated/By: 8-24-12 - Erman Caudill (Stantec)
Refer to accompanying Equation Reference document.

Stantec

Project Data (Optional):

Dam: *Baldwin Power Station*
Location: *Randolph County, Illinois*
Notes: *Scenario B - Tertiary Pond*

Inputs:

		English Units		*SI Units*	
Height of dam	h_d	22.0	feet	6.7	meters
Height of breach	h_b	22.0	feet	6.7	meters
Height/depth of water at breach	h_w	22.0	feet	6.7	meters
Storage	S	236.0	ac-feet	291101.7	m^3
Volume of water at breach	V_w	236.0	ac-feet	291101.7	m^3
Width of dam at base	W_{base}	140.0	feet	42.7	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		Overtopping			
Dam has core wall?		No			
Erosion resistant embankment?		No			

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

Average of Calculated Values:

Breach width	B_{AVG}	63.0	feet	19.2	meters
Breach bottom width	B_W	38.6	feet	11.8	meters
Breach formation time	t_f	0.4	hours	0.36	hours
Peak discharge	Q_p	23,774	ft^3/s	673.2	m^3/s
Breach side slope	Z	1.11		1.11	
Volume of embankment eroded	V_{er}	117819.0	ft^3	3336.4	m^3
Volume of water discharged	V_o,V_{out}	236.00	ac-feet	291101.7	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	0.343
16 - FERC 1987	0.550
17 - Froehlich 1987	0.459
18 - USBR 1988	0.211
19 - Von Thun and Gillette 1990	
20 - Von Thun and Gillette 1990	
21 - Von Thun and Gillette 1990	0.101
22 - Von Thun and Gillette 1990	0.219
23 - Froehlich 1995	0.360

Dam Breach Parameter Estimation
Earthen Embankment Comparative Spreadsheet
Last Updated/By: 8-24-12 - Erman Caudill (Stantec)
Refer to accompanying Equation Reference document.

Project Data (Optional):

Dam: *Baldwin Power Station*
Location: *Randolph County, Illinois*
Notes: *Scenario B - Tertiary Pond*

Inputs:

		English Units		SI Units	
Height of dam	h_d	22.0	feet	6.7	meters
Height of breach	h_b	22.0	feet	6.7	meters
Height/depth of water at breach	h_w	22.0	feet	6.7	meters
Storage	S	236.0	ac-feet	291101.7	m^3
Volume of water at breach	V_w	236.0	ac-feet	291101.7	m^3
Width of dam at base	W_{base}	140.0	feet	42.7	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		Overtopping			
Dam has core wall?		No			
Erosion resistant embankment?		No			

Data Convention:

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

Average of Calculated Values:

		English Units		SI Units	
Breach width	B_{AVG}	63.0	feet	19.2	meters
Breach bottom width	B_W	38.6	feet	11.8	meters
Breach formation time	t_f	0.4	hours	0.36	hours
Peak discharge	Q_p	23,774	ft^3/s	673.2	m^3/s
Breach side slope	Z	1.11		1.11	
Volume of embankment eroded	V_{er}	117819.0	ft^3	3336.4	m^3
Volume of water discharged	V_o,V_{out}	236.00	ac-feet	291101.7	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	164.8	5,816			
25 - SCS 1981	561.3	19,808			
26 - Hagen 1982	754.6	26,626			
27 - USBR 1982	645.9	22,791			
28 - Singh and Snorrason 1984	489.0	17,255			
29 - Singh and Snorrason 1984	657.0	23,183			
30 - MacDonald and Langridge-Monopolis 1984	450.7	15,906			
31 - MacDonald and Langridge-Monopolis 1984	1482.2	52,302			
32 - Costa 1985	1460.5	51,537			
33 - Costa 1985	430.2	15,182			
34 - Costa 1985	1543.4	54,463			
35 - Evans 1986	566.6	19,994			
36 - Froehlich 1995	263.0	9,282			
37 - Webby 1996	201.6	7,114			
38 - Walder and O'Connor 1997	427.7	15,093	298.5	55	5.03

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

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

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

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

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

USBR 1988

(9) $\mathrm{B} = 3\mathrm{h_w}$

Von Thun and Gillette 1990

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

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

$$\mathrm{C_b} = \mathrm{f(reservoir\ size, m^3)} = \left\{\begin{array}{cc} \textit{Size} & C_b \\ < 1.23\text{x}10^6 & 6.1 \\ 1.23\text{x}10^6 - 6.17\text{x}10^6 & 18.3 \\ 6.17\text{x}10^6 - 1.23\text{x}10^7 & 42.7 \\ > 1.23\text{x}10^7 & 54.9 \end{array}\right\}$$

Froehlich 1995

(12) $\overline{\mathrm{B}} = 0.1803\mathrm{K_o}\mathrm{V_w}^{0.32}\mathrm{h_b}^{0.19}$ 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) $0.25\ \mathrm{hr} \le \mathrm{t_f} \le 1.0\ \mathrm{hr}$

MacDonald and Langridge-Monopolis 1984

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

FERC 1987

(16) $0.10\ \mathrm{hr} \le \mathrm{t_f} \le 1.0\ \mathrm{hr}$

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

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

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

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

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

USBR 1988

(18) $\mathrm{t_f} = 0.011\mathrm{B}$

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

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

Other Equations:

Breach Bottom Width

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

Embankment Volume

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

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

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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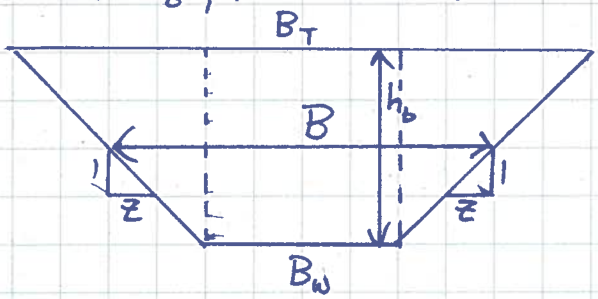
DAM BREACH EQUATIONS

DERIVATIONS NOT SHOWN

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



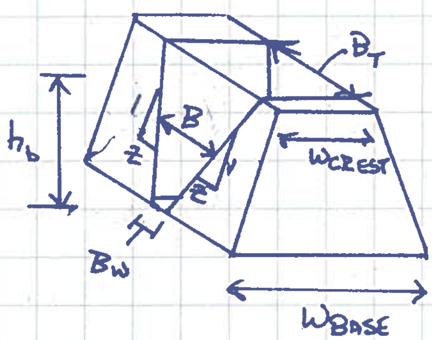
$$B = \frac{B_T + B_W}{2}$$

$$B_T = B_W + 2 h_b Z$$

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

$$B_W = B - h_b Z$$

2. VOLUME OF EMBANKMENT ERODED



AREA AT CENTER

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

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

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

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

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

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

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