Use of Flooding Probabilistic Risk Assessment

February 2020

Curtis L Smith
DISCLAIMER

This information was prepared as an account of work sponsored by an agency of the U.S. Government. Neither the U.S. Government nor any agency thereof, nor any of their employees, makes any warranty, expressed or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness, of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. References herein to any specific commercial product, process, or service by trade name, trade mark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the U.S. Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the U.S. Government or any agency thereof.
Use of Flooding Probabilistic Risk Assessment

Curtis L Smith

February 2020

Idaho National Laboratory
Idaho Falls, Idaho 83415

http://www.inl.gov

Prepared for the
U.S. Department of Energy
Under DOE Idaho Operations Office
Contract DE-AC07-05ID14517
Use of Flooding Probabilistic Risk Assessment

Dr. Curtis Smith, Director
Nuclear Safety and Regulatory Research Division
Idaho National Laboratory
Outline of my talk today

- SDP related to flooding in US
- Door integrity tests at Idaho State University
- Smoothed Particle Hydrodynamics for external flooding
- NRC-INL Flood Barrier project
SDP related to flooding in US
SDP related to flooding in US NRC

- Collected information from public NRC documents related to SDP for flooding
- NRC ROP includes determining safety significance of inspection findings through SDP
  - Specific hazards are evaluated → external flooding a challenge
  - Site-specific hazard that depends on geographical, meteorological, hydrological, and hydraulic information needed to characterize potential events relevant to the site
  - Limited data available to characterize PRA tools
- NRC technical guidance does exist
  - IMC 0609 Appendix A, Risk Assessment Standardization Project (RASP) handbooks
- Several events have been evaluated
- Items that correlate back to application of PRA
  - Modeling of flooding sequences
  - Quantification of SSCs and flood protection that are credited in specific scenarios
  - Evaluation of operator manual actions outside the control room involving flood mitigation
Examples of flood SDP

• **Oconee Standby Shutdown Facility (ML14058A051)**
  - Open penetration into SSF for two years
  - Opening below maximum flood height identified by licensee (5 feet)
  - Susceptible to up-stream dam failure
    - Independent analysis indicated 12 feet flood possible
    - Analysis indicated possible WHITE finding

• **Fort Calhoun Flooding Strategy (ML15152A315)**
  - January 2010, NRC identified inadequacies of buildings protection against floods
    - Site flood protection strategy may not be fully effective during scenarios
    - NRC determined that a “Yellow” finding was appropriate
  - Specific challenges associated with flooding after Fukushima were highlighted
    - Credit for hardening a facility prior to flood waters affecting the site
    - Assessing credit for limited available actions during a flood scenario based on timing availability (e.g., procuring additional equipment during or after the flood)
  - Consideration of information provided by licensee via qualitative IMC 0609 Appendix M approach in SDP was also evaluated and the finding was reaffirmed as “Yellow”
Door integrity tests at Idaho State University
The Portal Evaluation Tank (PET)

- PET is a semi-cylindrical 7,500 liter capacity steel tank
- An opening environment of 2.4 x 2.4 m for installation
- PET is connected through 3 in. PVC pipe to a 5 Hp. submersible pump
  - Located inside a 30,000 liter water reservoir
- Instrumentation
  - Electronic flow meter
  - Ultrasonic sensor
  - Pressure transducer
  - Pressure Gauge
Flooding Fragility Experiments

- A door frame was constructed using building code and decreased stud spacing
- Initial tests used hollow core doors and involved water rise until catastrophic failure occurred or leak rate equalization

Full Scale Tests – (Inward Orientation)

![Graph showing water height vs. run time with data points for Test 3 and Test 4, and a line indicating floor height.]

(a) (b) (c) (d)
PET Video Demonstration
Flooding Bayesian Analysis

- One of the complications for the flooding fragility modeling is the variety of observable phenomena related to the flood itself
  - Some thought should be given to which factors might be the most important
- An advantage of the Bayesian quantification approach is parameters in the regression model associated with unimportant factors should be found to be negligible
Work Using PET Data

- Eight complete sets of data
  - Depth at failure or greatest depth achieved
  - Average flow rate
  - Average temperature
- Door failure when damage is permanent & leakage increases in a short time (1)
- Success when an equilibrium state is reached between the flow and leakage rate (0)
- Also moved on to testing metal doors

<table>
<thead>
<tr>
<th>Depth (in)</th>
<th>Flow Rate (gal/min)</th>
<th>Temp (°F)</th>
<th>Failure</th>
</tr>
</thead>
<tbody>
<tr>
<td>23.23</td>
<td>291.5</td>
<td>65.98</td>
<td>0</td>
</tr>
<tr>
<td>20.75</td>
<td>292.5</td>
<td>67.04</td>
<td>0</td>
</tr>
<tr>
<td>42.3</td>
<td>292.5</td>
<td>66.02</td>
<td>1</td>
</tr>
<tr>
<td>21.05</td>
<td>297</td>
<td>67.67</td>
<td>0</td>
</tr>
<tr>
<td>24.22</td>
<td>294.5</td>
<td>66.6</td>
<td>0</td>
</tr>
<tr>
<td>35.41</td>
<td>292.5</td>
<td>66.87</td>
<td>1</td>
</tr>
<tr>
<td>40.76</td>
<td>291</td>
<td>68.33</td>
<td>1</td>
</tr>
<tr>
<td>38.85</td>
<td>294</td>
<td>68.14</td>
<td>1</td>
</tr>
</tbody>
</table>

INL-EXT-18-45247 - Nuclear Power Plant Component Flooding Fragility Research
Example of Flooding Model

- The fragility model for this case looks at seven possibilities:

1. $\text{logit}(p) = \text{int} + aD + bF + cT$

2. $\text{logit}(p) = \text{int} + aD$

3. $\text{logit}(p) = \text{int} + bF$

4. $\text{logit}(p) = \text{int} + cT$

5. $\text{logit}(p) = \text{int} + aD + bF$

6. $\text{logit}(p) = \text{int} + aD + cT$

7. $\text{logit}(p) = \text{int} + bF + cT$

```{r}
#Flow Rate (F), Depth (D), and Temperature (T) Model
model {
  for(i in 1:tests) {
    failure[i] ~ dbin(p[i])
    # Regression model
    logit(p[i]) <- int + a*flow[i] + b*depth[i] + c*temp[i]
    # failure.rep[i] ~ dbin(p[i], num.tested)  # Replicate values for model validation
    # diff.obs[i] <- pow(failure[i] - num.tested*p[i], 2)/(num.tested*p[i]*(1-p[i]))
    # diff.rep[i] <- pow(failure.rep[i] - num.tested*p[i], 2)/(num.tested*p[i]*(1-p[i]))
  }
  #chisq.obs <- sum(diff.obs[])
  #chisq.rep <- sum(diff.rep[])
  #p.value <- step(chisq.rep - chisq.obs)
  # Prior distributions
  int ~ dnorm(0, 0.0001)
  a ~ dnorm(0, 0.001)
}
data
data(list(tests=8,
  flow = c(291.5,292.5,292.5,297.294.5,292.5,291.294),
  depth = c(23.23,20.75,42.3,21.05,24.22,35.41,40.76,38.85),
  temp = c(65.98,67.04,66.02,67.67,66.6,66.87,68.33,68.14),
  failure = c(0,0,1,0,0,1,1,1))
inits
list(int=0, a=0)
```
Results for the Cloglog equations

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Equ. 1</th>
<th>Equ. 2</th>
<th>Equ. 3</th>
<th>Equ. 4</th>
<th>Equ. 5</th>
<th>Equ. 6</th>
<th>Equ. 7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>10.84</td>
<td>-107.5</td>
<td>4.832</td>
<td>5.301</td>
<td>5.847</td>
<td>1.222</td>
<td>1.88</td>
</tr>
<tr>
<td>a</td>
<td>47.88</td>
<td>3.705</td>
<td>-</td>
<td>-</td>
<td>45.31</td>
<td>35.61</td>
<td>-</td>
</tr>
<tr>
<td>(depth</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>coeff)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>b</td>
<td>-10.84</td>
<td>-</td>
<td>-0.01814</td>
<td>-</td>
<td>-4.648</td>
<td>-</td>
<td>0.02401</td>
</tr>
<tr>
<td>(flow rate</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>coeff)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>c</td>
<td>25.86</td>
<td>-</td>
<td>-</td>
<td>-0.08646</td>
<td>-</td>
<td>-15.89</td>
<td>-0.141</td>
</tr>
<tr>
<td>(temp</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>coeff)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DIC</td>
<td>0.01568</td>
<td>0.2372</td>
<td>12.68</td>
<td>13.25</td>
<td>0.0174</td>
<td>0.0203</td>
<td>13.51</td>
</tr>
</tbody>
</table>

- Deviance Information Criterion (DIC) can be used to examine the relative fit of a model
  - Measure of relative goodness of fit
  - Smallest DIC indicates the best fitting model
Pipe break tests

- ISU also performed tests to better understand water spray for breaks in pipes
SPH for External Flooding
Smoothed Particle Hydrodynamics

- A way to simulate flooding scenarios is needed
- Smoothed Particle Hydrodynamics (SPH)
  - Particle based method
  - Originally developed for astrophysics applications in 1977
  - Later extended for fluid dynamic applications
- SPH allows for flooding scenarios to be simulated
  - Does not confine fluid to meshes
  - Allows for a natural flow to be modeled
- A reliable SPH code is needed
  - Compare to experimental results
Introduction: SPH

• **Particles**
  – A particle is a minute fragment or quantity of matter

• **Usual meanings in science**
  – Smallest constituents of matter (Standard Model)
  – Nanoparticles, colloidal particles
  – Dust, powder, ashes
  – Sediment grains, water droplets

• **The duality of ’particles’ in SPH**
  – They are material points
  – They have volume, mass, pressure, density, etc.
Introduction: SPH Interpolation

- Particle $a$ has position $r_a$, mass $m_a$, volume $V_a$, etc.
- Particle Interactions are computed using the 'kernel' $w(r)$
- The support of $w$ has size $2h$, $h =$ smoothing length, $w$ is normalized

$
\int w(r) \, dr = 1
$

Ogee Spillway Comparison

- **Comparison Model**
  - Ogee spillway with horizontal apron
  - Details of experiment provided in Flow over Ogee Spillway: Physical and Numerical Model Case Study by Bruce M. Savage and Michael C. Johnson
  - Experiment details (scaled model):
    - Measurements taken 2 m upstream
      - Flow Rate
      - Total Head
    - Ten different runs conducted
  - Prototype scale was used for the SPH comparison which required scaling the model scale up 30 times
Neutrino Model

- Developmental SPH code Neutrino was used to conduct the comparison
- Model construction process:
  - Determine how to fill particles behind the spillway
  - Reduce leakage
  - Determine particle emitter location to set total head
  - Determine particle emitter location to set flow rate instead
  - Conduct parametric studies on model width and particle size
  - Reduce leakage again
  - Change particle emitter types
## Comparison Results

<table>
<thead>
<tr>
<th>Run</th>
<th>Flow Rate</th>
<th>Physical Total Head Result</th>
<th>SPH Total Head Result</th>
<th>Relative Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.9 m²/s ± 0.25%</td>
<td>24.3 m</td>
<td>24.9 m</td>
<td>2.4 %</td>
</tr>
<tr>
<td>2</td>
<td>6.0 m²/s ± 0.25%</td>
<td>25.3 m</td>
<td>26.7 m</td>
<td>5.5 %</td>
</tr>
<tr>
<td>3</td>
<td>12.3 m²/s ± 0.25%</td>
<td>26.5 m</td>
<td>27.5 m</td>
<td>3.7 %</td>
</tr>
<tr>
<td>4</td>
<td>19.0 m²/s ± 0.25%</td>
<td>27.4 m</td>
<td>28.6 m</td>
<td>4.4 %</td>
</tr>
<tr>
<td>5</td>
<td>27.9 m²/s ± 0.25%</td>
<td>28.5 m</td>
<td>30.0 m</td>
<td>5.5 %</td>
</tr>
<tr>
<td>6</td>
<td>37.8 m²/s ± 0.25%</td>
<td>29.5 m</td>
<td>31.3 m</td>
<td>6.2 %</td>
</tr>
<tr>
<td>7</td>
<td>48.2 m²/s ± 0.25%</td>
<td>30.4 m</td>
<td>32.8 m</td>
<td>7.7 %</td>
</tr>
<tr>
<td>8</td>
<td>58.9 m²/s ± 0.25%</td>
<td>31.4 m</td>
<td>34.1 m</td>
<td>8.9 %</td>
</tr>
<tr>
<td>9</td>
<td>73.8 m²/s ± 0.5%</td>
<td>32.4 m</td>
<td>33.7 m</td>
<td>4.0 %</td>
</tr>
<tr>
<td>10</td>
<td>89.9 m²/s ± 0.5%</td>
<td>33.5 m</td>
<td>35.3 m</td>
<td>5.4 %</td>
</tr>
</tbody>
</table>
How to Join Physics Model & System Model

• **Good** - Run repeated simulations and add the failure information into the existing static models

• **Best** – Dynamic PRA model that can interact with the simulation
  – No corrections needed for time dependent calculations
  – Determine average or mean time of particular outcomes
  – Analyze time order of failures to determine early protection methods
Enabling Conditions
Flood
Plant SSC Response to Initiator
SSC Failures & Successes

Risk Analysis Steps for Scenario Generation

3D Models for the Facility including Systems, Structures, & Component (SSC)

Scenario Simulation

Probabilistic events
Seismic
Flooding
Hazard Freq.
Static/Dynamic Loads
Debris
Water Migration
Fragilities

Computational Layers Used for the Analysis

Thermal-hydraulics
Timing is Everything

- Physics simulation are dynamic and time dependent
- Control logic is not always available in simulations
- Need to modify the behavior of the simulation at during execution.
Modeling Options

- **Time Steps**
- **Next event in time (EMRALD)**

Dynamic probabilistic risk assessment (PRA) model based on a three-phased discrete event simulation

To begin, add initial start states to Current and New States List

1. While there are States in the New Sates list, 
   For each State :
   - Add the Events to the Time Queue or Conditional List. 
   - Execute any Immediate Actions

2. If any Conditional Events criteria is met. 
   - Execute that events action/s. 
   - (Go to Step 1)

3. Jump to the next chronological event. 
   - Process that event’s actions. 
   - (Go to Step 1)
River flood modeling

- INL/EXT-15-37091, Flooding Capability for River-based Scenarios
- Evaluated two different types of potential river-based flooding tools
  - 1D/2D grid based (GeoClaw, EPA’s SWMM code, and Army Corps HEC)
  - 3D particle based
  - Both the 2D and 3D methods have positives and negatives
- Combination of both seems to be best approach moving forward
Dam break and subsequent river flood

by
Steve Prescott (INL)
Ram Sampath (Centroid Lab)
Donna Calhoun (BSU)
NRC-INL Flood Barrier Project
Project overview

- Project will identify and assess options and develop strategies for testing nuclear power plant (NPP) flood barriers
  - Including permanent components such as flood penetration seals, water tight doors as well as temporary flood protection features
  - Flood barriers external to the plant (e.g., earthen berms, aqua berms, sandbags) are not a focus of the review
  - Will look for information that may be useful when developing strategies for testing (e.g. prospects for harvesting, in-situ non-destructive testing or enhanced inspection, in-situ destructive testing)

- Project is part of NRC’s Probabilistic Flood Hazard Assessment (PFHA) Research Program

- Looking at decommissioning plants for likely source for harvesting
  - Visited Oyster Creek during December 2019

- Recently completed draft report → Goal to publish NUREG

- Will be supporting flood barrier testing workshop during the week of the NRC Regulatory Information Conference
  - Thursday and Friday (March 12-13)
Curtis.Smith@inl.gov

Thank you!