Improving Risk Assessments for Coal Combustion Residual Impoundment Dikes and Dams

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INTRODUCTION

The “wet” handling, transport and disposal of coal combustion residuals (CCRs) are common practice within the electric generating industry. The CCRs, including fly ash, bottom ash, coal slag and flue gas desulfurization (FGD) gypsum, are mixed with water and pumped as slurry to surface impoundments to allow for settling. The US Environmental Protection Agency (EPA) has identified approximately 700 individual wet CCR impoundments at over 200 facilities within the United States.[1] These impoundments are often formed by the construction of dikes and dams and are regulated by various state dam safety or solid waste programs.

On December 22, 2008, a failure of the Dredge Cell 2 containment dike at the Tennessee Valley Authority’s Kingston Fossil Plant released an estimated 4.1 million cubic meters of coal ash and water into the surrounding area. Evidence of the resultant flood wave was discovered up to 1,000 meters from the facility.[2]

Following the Kingston incident, state regulatory agencies, the US EPA and the power generating industry have placed a renewed focus on the dam safety programs associated with CCR impoundment dikes and dams. A key element of a dam safety program is the development of hazard classifications for each structure. These classifications assess the potential impacts caused by a dam breach and focus on the potential for life loss or environmental and economic damage.

Dam safety hazard classifications are often codified within a state’s dam safety program and require specific design standards, as well as operation, maintenance and inspection procedures. Efforts to determine a hazard classification can vary from a simple review of topographic and aerial mapping in remote or isolated areas to detailed breach analyses, including hydrologic and hydraulic modeling. Dam breach models are typically used when potential impacts to downstream populations and infrastructure are identified.

Traditional dam breach modeling methodologies typically consist of one-dimensional flow models and assume the breach material behaves completely as water. Application of these traditional methods to risk assessments of CCR impoundment facilities may result in inaccurate results that over- or under-predict breach hazard limits and severity. Over-prediction of breach impacts may result in an increase in the dam hazard classification, requiring expensive and unnecessary facility upgrades; under-prediction of the hazard could result in inadequate emergency action planning and disaster preparedness.

This paper will discuss the issues associated with traditional breach modeling methodologies and outline methods and procedures for an improved methodology. In particular, focus will be on the application of a two-dimensional hydraulic breach routing model to simulate CCR impoundment breaches as hyper-concentrated sediment flow. A case study is presented and recommendations for additional study are provided.

TRADITIONAL DAM BREACH METHODS

Modelers have several options for dam breach studies. Prevalent hydrologic and hydraulic engineering software, including the US Army Corps of Engineers' HEC-HMS and HEC-RAS platforms and the National Weather Service's DAMBRK, include dam breach analysis tools. For several reasons, these applications can be considered the traditional and preferred methods for dam breach studies. These software packages are considered the industry standards for hydrologic and hydraulic modeling have a large knowledge base and have been successfully utilized for many dam breach scenarios, including: flood control, water supply, hydropower and irrigation dams. For trained modelers, these applications can allow for the efficient creation of watershed and stream models to simulate and interpret the unsteady flow of a breach hydrograph and its downstream impacts.

LIMITATIONS OF TRADITIONAL DAM BREACH METHODS

The traditional models may only be accurately applied to scenarios which can reasonably be constructed within their one-dimensional model framework, such as the routing of breach hydrographs through well-defined channels. Also, the models simulate the creation and routing of a breach hydrograph composed only of water. For some breach scenarios and landscapes, these limitations may produce unrealistic or inaccurate results.

One-dimensional flow models are best applied to channelized flow, such as rivers, streams and canals. CCR impoundments are often constructed as self-standing facilities with perimeter ring dikes in flat areas, rather than conventional upland reservoirs with dams constructed across stream valleys. Since ring dikes or multi-sided facilities can fail at any location along their perimeter, methods need to be utilized that predict breach flow run-up across adjacent valleys, not only through a defined channel. Also, in some landscapes where the channel is adjacent to a dam, a breach wave may flood across the valley, as well as up and downstream. The breach flow from the Kingston, TN incident easily overtopped adjacent channel banks and proceeded to travel across the floodplain. [2]

CCR impoundments can vary significantly in the ratio of free water to solids stored. Depending on this ratio, the impounded materials may have flow characteristics which differ significantly from a purely water flow, exhibiting non-Newtonian fluid or solid flow characteristics, which will affect the development of the breach hydrograph, as well as the downstream routing of the flood wave.

Modeling procedures that assume water-only releases from a CCR impoundment failure may over estimate release volumes since it is generally assumed that all water volume stored above the simulated breach elevation will be evacuated. A study conducted on the historic breaches of mine tailings dam failures, which are operated similarly to CCR impoundments, by M. Rico, G. Benito and A. Diez-Herroro [3] indicated that past failures evacuated similar fractions of impounded solids. In this study, tailings' volumes stored at the time of failure were found to have a strong correlation ($r^2 = 0.86$) with the tailings outflow volume, with roughly 35% of the stored volume of solids being discharged during a failure. Similarly, the December 2008 Kingston, TN incident released approximately 35% of the impounded ash material. The breach also exhibited flow properties significantly different than the behavior of a pure water failure. Although every failure of this type of facility won't produce exactly 35% volume, these past studies indicate that the released volume will likely be substantially less than from the failure of an impoundment that stores only water.

Along with over-estimations of breach volumes, water-only hydraulic simulations will likely route the full breach hydrograph more rapidly than a sediment-water mixture. While the release of the initial free water volume sitting above the impounded solids and displacement of downstream water bodies could result in an initial fast-moving flood wave, the majority of the impounded materials, comprised of saturated solids, can be expected to exhibit characteristics of viscous fluid motion. Water-only hydraulic simulations may predict faster arrival times to downstream areas and lower depths closer to the impoundment as the breach volume is routed more readily.

IMPROVED BREACH ROUTING METHOD

In order to provide more accurate and reliable breach simulations for CCR facilities, multiple publicly- and commercially-available software applications were reviewed. Specifically, modeling software was evaluated based on its capabilities to route unsteady flows two-dimensionally and take into account the semi-solid properties of a slurry or mud. FLO-2D, a volume conservation flood routing model published by FLO-2D Software, Inc. met these criteria.[4]

Building a two-dimensional model requires similar data as a one-dimensional model. Each model requires an elevation dataset. While a one-dimensional model requires cross sections, a two-dimensional model uses elevation information in the form of a Digital Terrain Model (DTM) to develop a grid. Grid cells are assigned a Manning's roughness coefficient just as roughness values would be assigned to cross sections. Upstream and downstream boundaries, inflow hydrographs and simulation parameters are required in both types of models.

Although the data requirements for either model platforms are similar, if flow is not primarily one-dimensional, the differences in the results are quickly apparent. A two-dimensional model can route flow in multiple directions over a relatively flat landscape, which allows for the simulation of a breach flood wave fanning out across a floodplain as depicted in Figure 1. A two-dimensional model also allows flow to vary in depth along the width of a wide channel or show run-up as a flood wave accesses a channel from directions perpendicular to its alignment.

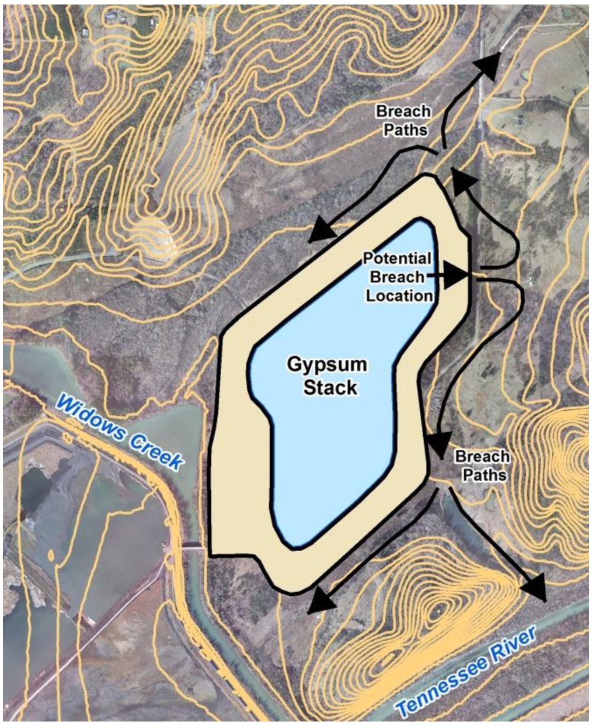

Figure 1. Illustration of potential flow paths from a single breach location at a CCR facility.

The second critical tool for simulating a breach of a CCR impoundment is the capability to model the flow as a solid-water mixture. As the failure at Kingston demonstrated, water is not the only material which will flow during the breach of CCR impoundments. The discharged material during the Kingston failure was extremely viscous and acted more like a mudflow than water, depositing CCR material in a wide fan around the breach location. A more realistic model will allow for the simulation of viscous hyper-concentrated sediment flows often referenced to as mud or debris flows.

At sufficiently high concentrations of sediment, the flow stops acting as a Newtonian fluid. Sediment concentrations by volume below 0.20 typically still act as water while concentrations by volume above 0.65 may not flow at all or may move as near solid masses.[5] Material with sediment concentrations falling between this range can be expected to act as mud floods, mud flows or landslides.

To conduct a hyper-concentrated sediment flow simulation, several parameters are required including specific gravity, laminar flow resistance and coefficients and exponents in equations relating viscosity and yield stress to sediment concentration. Specific gravity can be obtained through laboratory testing of sediment samples. Laminar flow resistance can be selected based on published guidance which provides typical ranges of values for various floodplain cover materials ranging from asphalt to meadows.[5] The coefficients and exponents for defining the viscosity and yield stress relationships can be selected by comparing site specific properties, including particle size distribution, to published material property data, such as those by O'Brien and Julien (1988) [6] or performing material specific laboratory testing.

As expected, simulations utilizing two-dimensional hyper-concentrated sediment flow capabilities show substantial differences when compared to the traditional water-only one-dimensional approaches. The saturated solid materials discharged from a potential breach move at slower rates than water. Since the breached volume flows less readily, the areas near the breach are inundated to greater depths and may remain inundated permanently as the flow eventually comes to a rest, rather than continuing to flow downstream.

WIDOWS CREEK CASE STUDY

A case study that highlighted the benefits of the improved approach and the limitations of the traditional dam breach analysis techniques is the analysis of the potential impact of a dam failure at the Gypsum Stack at Tennessee Valley Authority (TVA) Widows Creek Fossil Plant (WCF) in Jackson County, Alabama. TVA's goal in analyzing a breach of the WCF Gypsum Stack was be to assess the potential risk to people, property and the environment from a failure of the dike surrounding the facility and take steps to mitigate those risks. Potential mitigation actions could include operational changes to the facility or acquisition of at-risk properties.

The WCF Gypsum Stack facility has a footprint of approximately 50 hectares, standing approximately 25 meters tall. The Gypsum Stack facility is a free-standing facility located in a wide floodplain. Widows Creek to the west of the facility is the only channel near the facility, with low lying rural residential areas immediately adjacent to facility on multiple sides. The majority of the facility is composed of sluiced gypsum which is saturated due to a shallow overlying surface impoundment. The properties of the WCF

Gypsum Stack therefore presented two issues when attempting to apply traditional dam breach methodology to the analysis: Flow in the event of a breach would not be contained in local channels and would be routed in several directions, and the majority of the discharged volume would be a saturated gypsum mud or slurry, rather than strictly water.

An initial routing model was developed using HEC-RAS. This initial analysis utilized the HEC-RAS software to model split flow and simulated the breach as water. A review of initial model results identified concerns regarding the inability to capture the extent of flow run-up across the channel and the estimated extents of the run-out in the floodplain areas.

The improved breach routing methods were then applied to simulate a failure of the WCF Gypsum Stack. Geotechnical and laboratory testing results of the sluiced material were utilized to select the appropriate material parameters for the hyper-concentrated sediment flow tools in the FLO-2D software. Topographic data and land cover data sets were utilized in the development of the elevation and roughness grids. Finally, the breach hydrograph was routed through the model with a defined solid-to-water ratio of approximately 50% by volume based on an assumed worst-case scenario, fully-saturated condition.

With these assumptions, the behavior of the modeled breach of the WCF Gypsum Stack appeared very similar to the observed aftermath of the Kingston failure. Since the breach traveled at slower rates than a water only simulation, it did not flow away from the breach location as rapidly, thus inundating areas near the facility to a greater depth. The breached material continued to creep for several hours after the occurrence of the breach before finally coming to a rest, as shown in an example of one analyzed breach location in Figure 2. In comparison, a traditional dam breach simulation, performed using HEC-RAS, over-predicted the velocity and distance traveled by the breach while under-predicting the severity of inundation at locations adjacent to the breach.

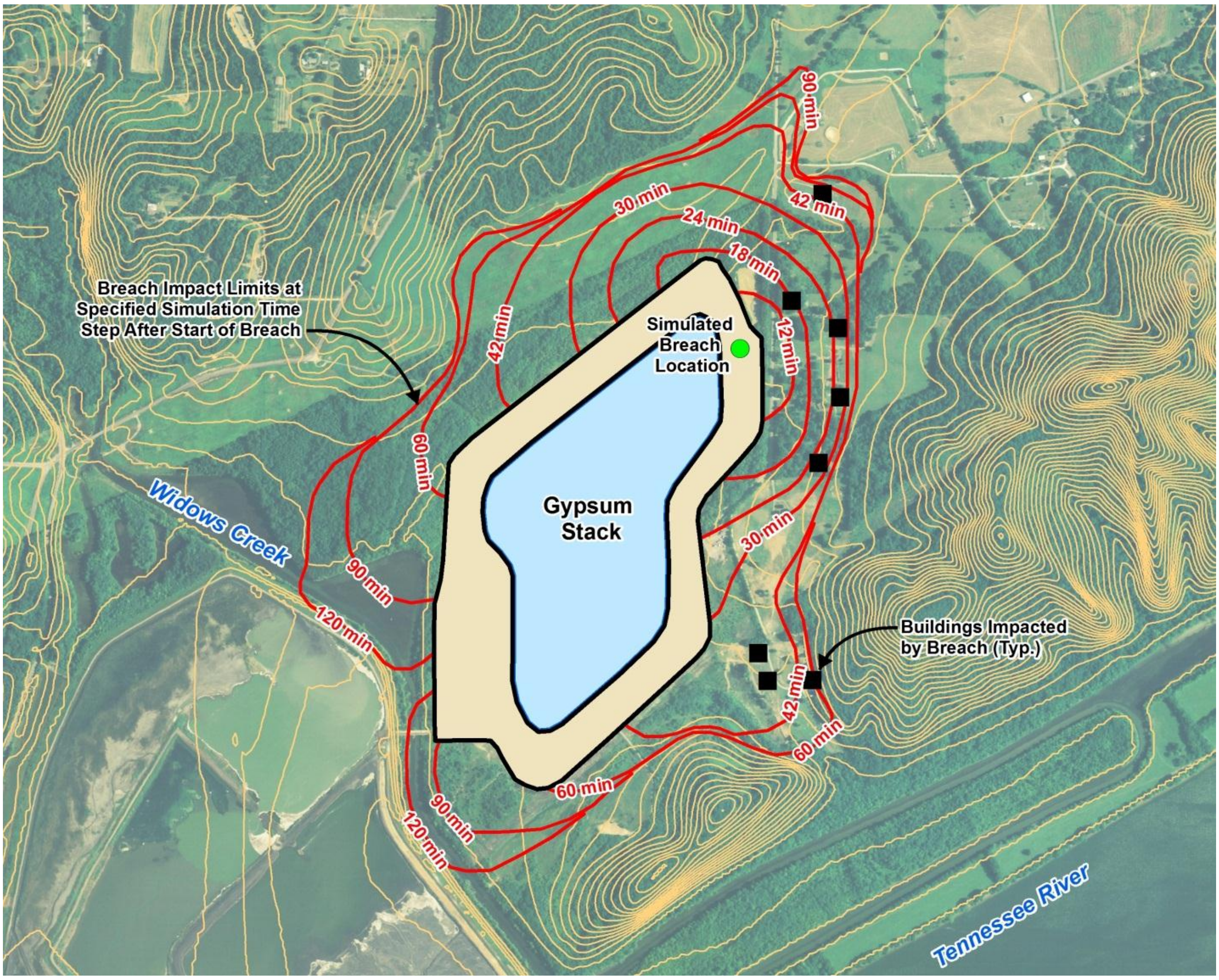

Figure 2. Results of the two-dimensional hyper-concentrated flow model displayed as estimated travel time of the initial flood wave, as measured from the start of the breach.

For this case study, multiple locations were chosen as potential breach locations with the results aggregated into a single inundation map shown in Figure 3. The most striking difference between the traditional one-dimensional water-only breach simulation and the two-dimensional hyper-concentrated sediment flow can be seen to the east of the WCF Gypsum Stack. The results of the improved breach routing methodology identified an additional five residences within the limits of inundation. TVA was able to utilize these improved results to identify mitigation activity priorities and reduce the risks to neighboring properties and infrastructure.

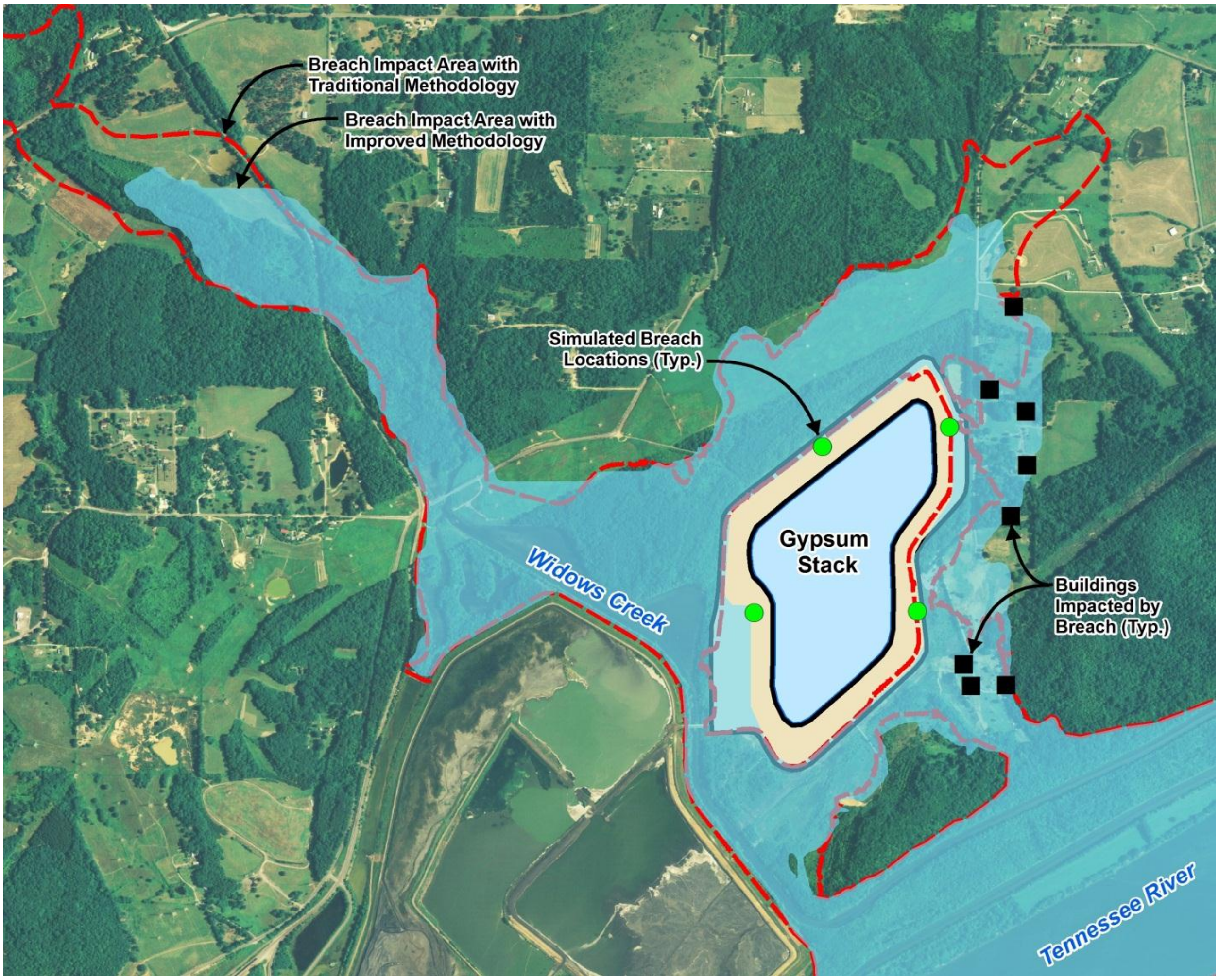

Figure 3. Comparison of the one-dimensional and two-dimensional breach results for the Widows Creek Gypsum Stack study. The potential inundation areas are a result of the aggregation of four breach simulations at different locations along the dike perimeter.

The management of existing CCR impoundments will continue to be an important issue within the electric power generating industry for the foreseeable future. Understanding the risks and potential liabilities associated with a failure of a facility will be a key to responsible and proactive management.

Dam breach analyses performed with two-dimensional hyper-concentrated flow model platforms can provide advantages over traditional breach modeling methods for a range of CCR impoundment conditions and settings. These scenarios include facilities which contain a high ratio of impounded solids to free water or those set in topography that would lack a single defined flow path.

It should be noted that rheologic data in published literature may not be appropriate for materials stored at other CCR facilities. Laboratory testing to develop viscosity and yield stress relationships to sediment concentration may be required for certain CCR materials. In addition, before utilizing the methodology described in this paper, the facility setting must be considered. For example, during the Kingston failure, the displacement of water in an adjacent shallow slough resulted in a large and extended "clear water" wave run-up with the slurry extents limited to a smaller area. These types of varied settings must be considered on an individual basis. Finally, a sensitivity analysis is recommended for each critical parameter related to hyper-concentrated sediment flow to ascertain the range of potential impacts and to account for uncertainty in final recommendations.

To expand upon the application of this methodology and extend the knowledge base, further studies could develop rheologic parameters for a wide range of CCR materials and saturation levels. In addition, application of this methodology to historic breach events such as Kingston or others would provide for further understanding of the field and help verify the use of models such as FLO-2D in simulating CCR impoundment failures.

REFERENCES

[1] US EPA. Coal Combustion Residues (CCR) – Surface Impoundments with High Hazard Potential Ratings, http://www.epa.gov/osw/nonhaz/industrial/special/fossil/ccrs-fs/index.htm, accessed 20 February, 2013.

[2] AECOM. Root Cause Analysis of TVA Kingston Dredge Pond Failure on December 22, 2008, Vernon Hills, Illinois, 2009.

[3] M. Rico, Benito G., and Diez-Herrero A. Floods from Tailings Dam Failures, J. Hazardous Materials, 2008, 154, pp. 79-87.

[4] FLO-2D Software, Inc. FLO-2D Flood Routing Model, Version 2009.06, 2009.

[5] FLO-2D Software, Inc. FLO-2D Reference Manual: Mud and Debris Flow Simulation, pp. 47-55, 2009.

[6] O'Brien, J. S. and Julien, P. Y. Laboratory Analysis of Mudflow Properties, J. Hydraulic Engineering, 1988, 114, pp. 877-887.