

# Coupled Dam Safety Analysis using BREACH and WinDAM

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## Abstract

*The National Weather Service BREACH model is a physically-based model to predict the discharge hydrograph resulting from a breached earthen dam [2]. Likewise, Windows™ Dam Analysis Modules (WinDAM) is a physically-based model and set of modular software components that can be used to analyze overtopping and internal erosion of embankment dams [6]. Dakota is an extensive software framework for design exploration and simulation [1]. These tools can be coupled together to create a powerful framework.*

*This paper describes several new interfaces that have been designed to conduct coupled analysis over a wide range of input parameters including both structural properties and flow properties. The goal of this paper is to describe how the new framework was designed to loosely couple the existing software, BREACH, WinDAM, and Dakota, and how the framework can be used to efficiently analyze spillway and dam erosion data.*

**Keywords:** Dam erosion analysis, hydraulic modeling, parameter study, risk assessment, simulation.

## 1. Introduction

Physically-based simulation models can be used to aid in the prediction of hydraulic and erosion processes which are associated with flow over an earthen dam or through an internal erosion channel. Two such models are the National Weather Service BREACH Model [2] and the WinDAM Models developed by USDA-ARS and Kansas State University (Temple, Hanson, Neilsen, 2006).

The BREACH Model can be used to simulate hydraulic flows over and through a dam, and estimate the breach potential for a given storm or inflow hydrograph. The model can also be used to estimate the resulting breach hydrograph and peak outflow.

Windows™ Dam Analysis Modules (WinDAM) is a set of modular software components that can be used to analyze overtopped earthen embankments and internal dam erosion. The development of WinDAM is staged. The initial computational model addresses routing of the flood through the reservoir with dam overtopping and evaluation of the potential for vegetation or riprap to delay or prevent failure of the embankment. The first module also includes auxiliary spillway erosion analysis. Unlike previous software, it

allows a user to analyze up to three auxiliary spillways and evaluate embankment erosion on the dam. The subsequent computational model, WinDAM B, incorporates dam breach analysis; i.e., the breach failure of a homogeneous embankment through overtopping and drainage of stored water in the reservoir. The third model, WinDAM C incorporates internal erosion analysis. In addition, work is currently underway to include analysis of non-homogeneous embankments, and analysis of other forms of embankment protection [7]. WinDAM is designed to address the dam safety and sustainability concerns facing the national legacy infrastructure of over 11,000 small watershed dams constructed with US Federal involvement over a seventy-year period. An important aspect of sustainability is risk analysis. The key elements of this analysis are to 1) identify the types of failures and their probabilities and 2) assess the outcome of each failure if it were to occur. To understand the effects of soil materials, embankment geometry, and reservoir characteristics, a process-based model, such as BREACH or WinDAM, is needed. However, even with these models, it can be a tedious task to analyze the effect of changes in each input parameter.

Dakota is an extensive software framework developed by Sandia National Laboratories for the design and analysis of computer experiments, including parameter studies, uncertainty analysis, sensitivity analysis, etc. [1]. In this paper, these tools and models are coupled together to create a powerful new framework. Several new interfaces have been developed to conduct coupled analysis over a wide range of input parameters including both structural properties and flow properties. The goal of this paper is to describe how this new framework can be used to loosely couple models from WinDAM and BREACH with Dakota driving the analysis, and how the framework can be used to efficiently analyze spillway and dam erosion data.

A set of hypothetical, synthetic dams is used to represent the range of USDA Small Watershed Structures by varying height and reservoir volume augmented by three variations of material properties. Outcomes of historical failure cases and physical model studies are compared with the synthetic set. The work by Tejral and Hunt suggests that WinDAM is predicting in the correct order of magnitude and exhibiting appropriate sensitivity to material parameters [5]. In this paper, we use the same synthetic set to show how the new framework enables users to perform the same analysis in a fraction of the time previously required.

## 2. Coupled Dam Analysis Framework

Hydraulic engineers are comfortable with the tools of the trade to develop Computational Models which are typically used to evaluate a single set of model input parameters defining both structural and hydraulic properties. If a user wants to determine which input parameters are the most important or influential in determining peak outflow, flow duration, or the amount of dam erosion that may result, the user is faced with the daunting task of executing the model many times after simply tweaking the input parameters and recording the output which results. The goal of our new framework is to minimize this tedium.

Dakota supports several different automated options for the Design and Analysis of Computer Experiments (DACE) as described by Adams, et. al, [1]:

- *Sensitivity Analysis (SA)* - determine which inputs have the most influence on the output.
- *Uncertainty Analysis (UA)* - compare the relative importance of model input uncertainties on output.
- *Uncertainty Quantification (UQ)* - take a set of distributions on the inputs and propagate them through the model to obtain distributions on the outputs.
- *Parameter Studies* – specify a range of input parameters and compute the corresponding output which can be displayed in text or graphical format.

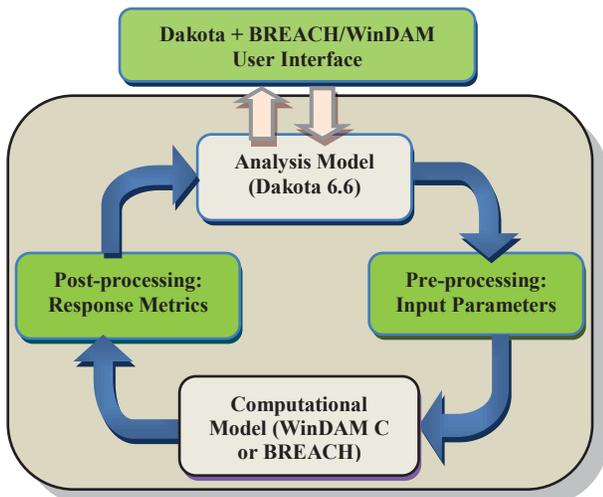


Figure 1: Iterative analysis with Dakota and models

Unfortunately, most hydraulic engineers are not well versed in the Dakota modeling language which is used to construct the Analysis Model as shown in Figure 1. To facilitate rapid analysis, we have developed an intuitive user interface to construct the Analysis Models, and a framework with parsers to automatically convert input parameters generated by Dakota into the fixed column format expected by the Computational Models, pre-process the models to generate input files for the model simulators, post-process the output generated by the simulators to extract the key parameters of interest. These parameters are then passed to Dakota to complete a single iteration as shown in Figure 1. Thus, the

framework, consisting of the green boxes, provides the glue to enable efficient analysis.



Figure 2: Internal erosion analysis at USDA-ARS HERU

In a Dakota input file, there are six specification blocks that may appear in the Analysis Model, and the blocks are identified using the keywords: environment, variables, interface, responses, model, and method. A model contains a set of variables, an interface, and a set of responses, and an iterator operates on the model to map the variables into responses using the interface. WinDAM C can be used to automatically generate Dakota input files for simple parameter studies on material properties. Then, Dakota is invoked to iterate on the WinDAM simulation models, or vice versa, as needed to generate output. Instead of having WinDAM drive the analysis, we can also use Dakota to drive the analysis iteratively as shown in Figure 1. In the previous result by Neilsen, we focused on simple parameter studies and one Computational Model, WinDAM C [3]. However, more complex analyses using several different models may be required to complete the analysis.

The new framework allows the user to choose between different Computational Models, WinDAM C or BREACH. The results from both models can be evaluated at the same time using comparable input parameters. In the next section, we detail an analysis based on a synthetic data set developed by Tejral and Hunt [5].

## 3. Synthetic Data Set

The primary purpose of WinDAM C is to extend analysis capability to include internal erosion models developed as a result of the type of empirical analysis as shown in Figure 3.

A synthetic data set was developed to evaluate different Computational Models over a range of different material properties and different erosion models ranging from a sand material which has High erodibility as shown in Figure 3, to a clay material with Low erodibility as shown in Figure 4.

Total Unit Weight (Tw) (lb/ft <sup>3</sup> )	120
Erodibility (Kd) (ft/h)/(lb/ft <sup>2</sup> )	70
Undrained Shear Strength (Us) (lb/ft <sup>2</sup> )	300
Critical Shear Stress (lb/ft <sup>2</sup> )	0

Figure 3: Silty sand (SM) bare material properties

In addition to a range of material properties, a user may want to evaluate a range of different dam configurations and sizes. For this synthetic analysis, a typical range of dam sizes are used ranging from a dam height of  $2^2 = 4$  feet (as shown in Figure 2) to a maximum of  $2^7 = 128$  feet, with appropriate dam crest, etc., and internal erosion originating at  $1/4^{\text{th}}$  of the dam height. For convenience, we introduce a scale variable ranging from 0 to 5 to represent dam heights of  $2^{(\text{scale}+2)}$  ft. Not surprisingly, stronger materials with less hydraulic flow results in much less erosion, in fact the same inflow resulted in no failure even after 72 hours for the same experiment shown in Figure 2 by using the clay material as shown in Figure 4.

Total Unit Weight (Tw) (lb/ft <sup>3</sup> )	130
Erodibility (Kd) (ft/h)/(lb/ft <sup>2</sup> )	0.3
Undrained Shear Strength (Us) (lb/ft <sup>2</sup> )	1700
Critical Shear Stress (lb/ft <sup>2</sup> )	0.2

Figure 4: Clay (CL) bare material properties

Evaluating the sand material on a 128 ft. dam results in the output showing a cross section of the dam from WinDAM C (128high.WDC) in Figure 5.

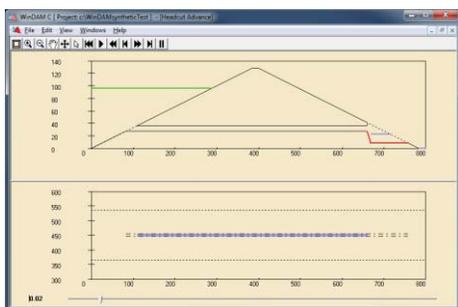


Figure 5: WinDAM C model output

The new interface shown in Figure 6 allows users to specify a range of input parameters to allow Dakota to vary the model inputs and perform different types of analyses including uncertainty quantification, sensitivity analysis, and parameter studies. For example, users can analyze a range of varying input parameters. From the UI, users just open an existing WinDAM C project, select the type of study, for example a simple multidimensional parameter study. Then, the user is prompted to specify a range of parameters denoting different materials as shown in Figure 6. The user can also specify the number of partitions in each dimension, or edit the generated Dakota input file directly.

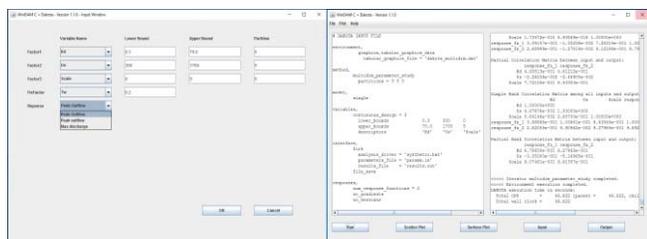


Figure 6: Dakota + BREACH/WinDAM User Interface

Then, the framework automatically generates the initial template of a Dakota input control file and template files with placeholders for the parameters to be varied. Finally, the user can simply click on the Run button to save the Dakota input analysis file, and fire up Dakota and WinDamSim (the Computational Model) to perform the analysis in this case using iterative analysis on  $6 \times 6 \times 6 = 216$  input data sets. The values for erodibility {Kd} and undrained shear strength {Us} are computed by Dakota sampling on fixed intervals at the end of each partition. Custom parsers are used to extract and format the data generated by Dakota, and a Dakota double-precision pre-processing tool, *dprepro*, is used to replace the tokens for {Kd}, {Us}, and {Scale} in the template file with the values in the parameter input file to generate a simulation input file to be processed by WinDamSim. A portion of a WinDAM C input file used in the synthetic study is shown below in Figure 7.

```

WINDAM      01/01/2009
OPTION      SIMPLE      BARESOIL      NOPS      INTERNAL
IEMODEL     2           120           0070.0000  1700.0000  0.2
HYD         0.0167     0           1C          10
0.02
...
ENDTABLE
CRESTPRFL
0           8
900        8
ENDTABLE
STROUT     6           0           ELEV
    
```

Figure 7: Input WinDAM C (.WDC) file

The corresponding template file is shown below in Figure 8. Note that the fields denoting the values for erodibility, Kd, and undrained shear strength, Us, are replaced with tags {Kd} and {Us}, respectively. Also, {Scale} is used to allow for the range of different dam geometries to be specified. The values for Scale range from 0 to 5; e.g., dam crests of 4 feet to  $4 \times 2^5 = 128$  feet.

```

WINDAM      01/01/2009
OPTION      SIMPLE      BARESOIL      NOPS      INTERNAL
IEMODEL     2           120           {Kd}      {Us}      0.2
HYD         0.0167     0           1C          10
0.02
...
ENDTABLE
CRESTPRFL
0           {4*(2**Scale)}
900        {4*(2**Scale)}
ENDTABLE
STROUT     { 3*(2**Scale) }      0           ELEV
...
CONDUIT    .2           .2           {(2**Scale)}      450
    
```

Figure 8: Generated WinDAM C template (.WDT) file

This processing can take place in parallel to reduce the overall computation time. Once the iterative analysis is complete, the output can be viewed in text or graphical format. In this example, tabular text data is stored in the file *dakota\_multidim.dat*. The peak outflow is shown below in Figure 9. A single template file can be used to represent a wide range of different input parameters representing both material properties and geometric properties. Graphs are

generated using Jzy3d [4]. Each surface below represents a different Scale from 0 (on the bottom) to 5 (on the top).

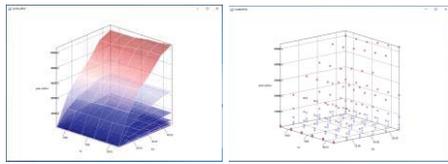


Figure 9: Surface and scatter graphs for peak outflow

The parameter study can be extended to perform uncertainty quantification by making a few small changes to the input. The resulting output confirms a strong positive correlation between Kd and peak discharge and a small negative correlation between Us and maximum discharge. The same framework can also be used to evaluate input files from an existing BREACH project. The corresponding BREACH variables, such as {HI}, {HU} and {Scale} can be automatically parameterized as shown in Figure 10, and response variable is set to {MaxOutflow}.

```
DAM
{HI      } {HU      } 0.      {(2**Scale)}.
0.      60.      0.02     0.9
...
```

Figure 10: Generated BREACH template (.DATT) file

This processing can take place in parallel to reduce the overall computation time. Once the iterative analysis has been completed on all 75 input files, the output can be viewed in text or graphical format as shown in Figure 11.

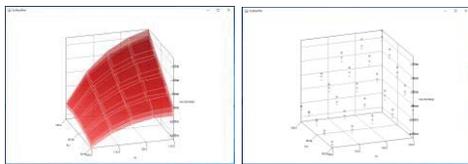


Figure 11: Graphs for max outflow in BREACH

The resulting output confirms a strong positive correlation between HU and maximum discharge and a strong positive correlation between HI and maximum discharge.

### 4. Conclusions

For comparison with the previous analysis on the synthetic dam set [5], we construct a peak breach discharge versus dam height plot using three different levels of erodibility

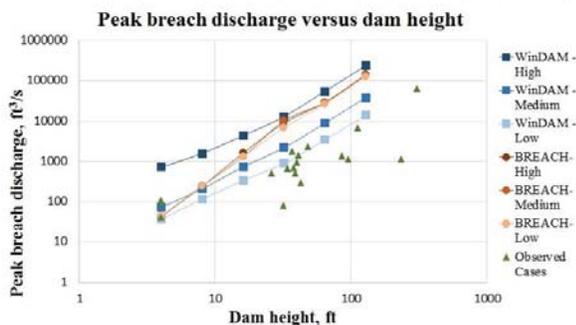


Figure 12: Peak breach discharge versus dam height

(High, Medium, and Low) for both WinDam C and BREACH. Cases are failure cases from Wahl (1998) and ARS research. As shown in Figure 12, the results mirror the results of previous research, but at a fraction of the cost in terms of time required to complete the analysis.

WinDAM is being developed in stages to evaluate the performance of earth dams. Existing modules with well-defined interfaces enable efficient integration of existing legacy software with new innovations. The system provides tools that can be used to better understand the structure, function, and dynamics of water control structures. This paper describes how WinDAM and BREACH models can be analyzed efficiently using a novel new Dakota interface. The next step will be to couple CFD flow models with physical models to model the erosion that results from the given flows. Efficient, high-level analysis can still be performed by combining these new models with Dakota.

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