

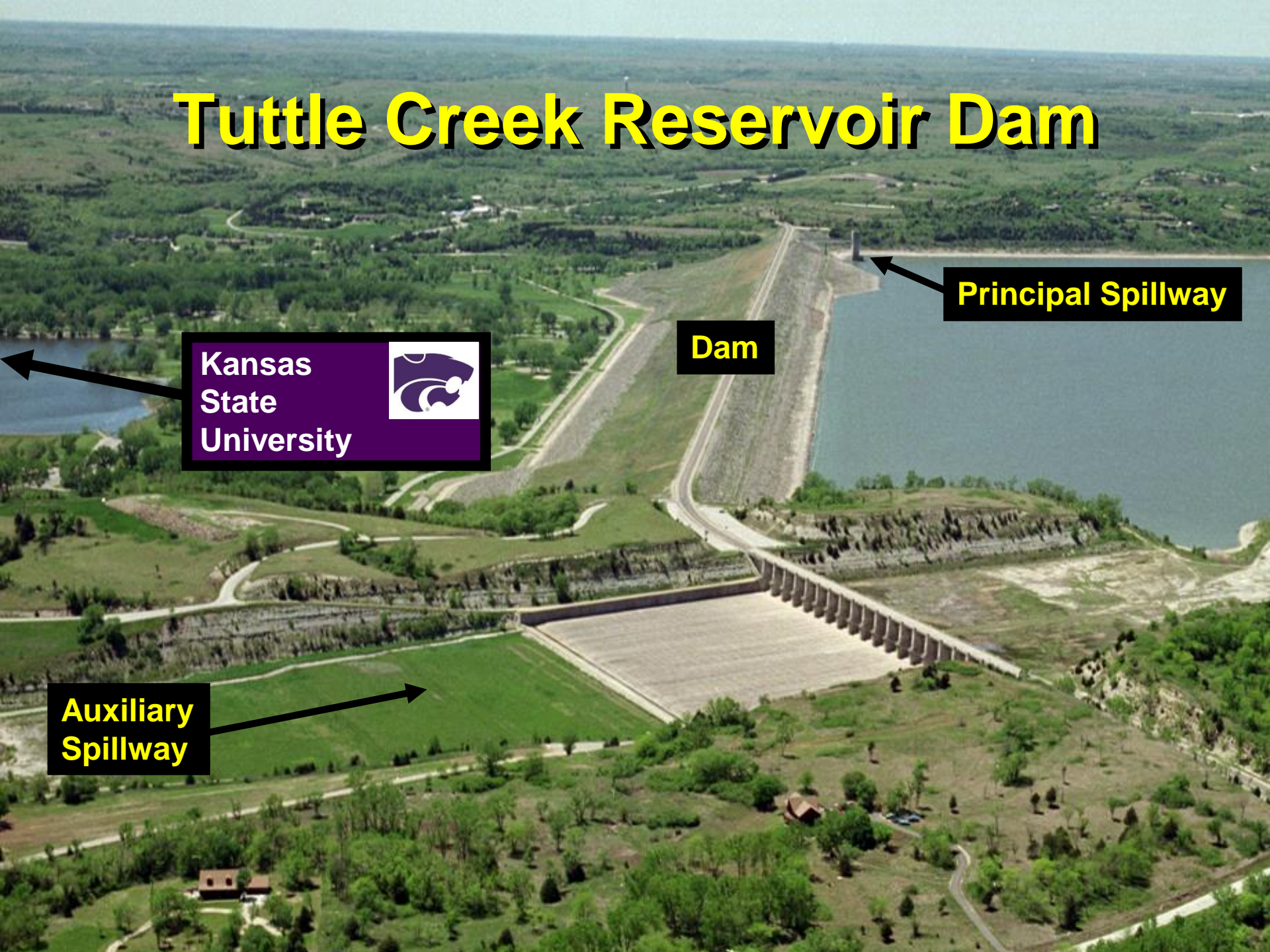
Sensitivity Analysis of Internal Erosion Models for Dam Safety

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Tuttle Creek Reservoir Dam



Principal Spillway

Dam

**Kansas
State
University**



**Auxiliary
Spillway**

Auxiliary Spillway Discharge (1993)



- Peak Flow: 60,000 cfs = 1,700 cms
- Duration: 21 days



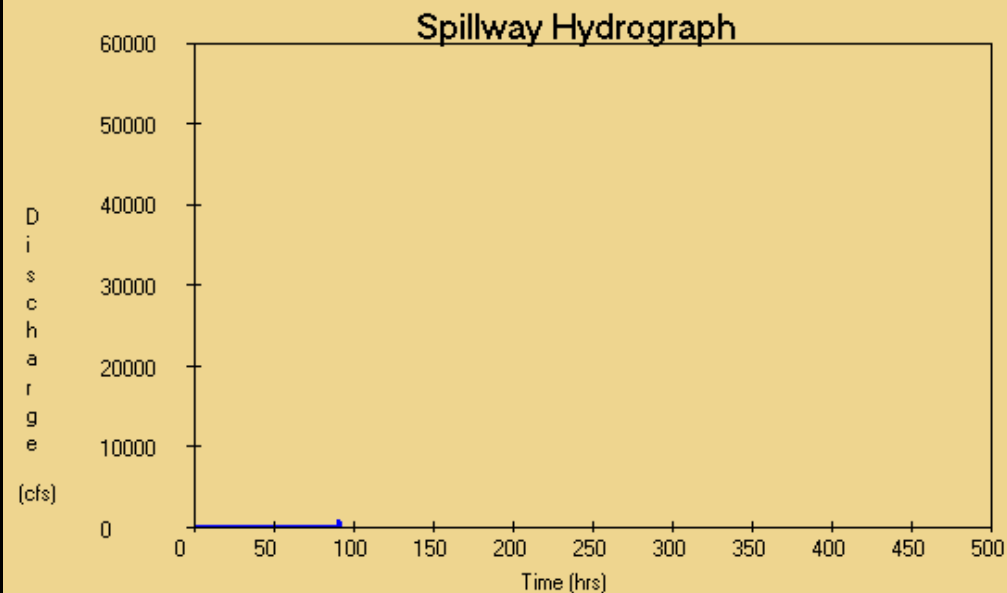
Auxiliary Spillway Erosion (1993)



Erosion: 400,000 yd³
307,000 m³

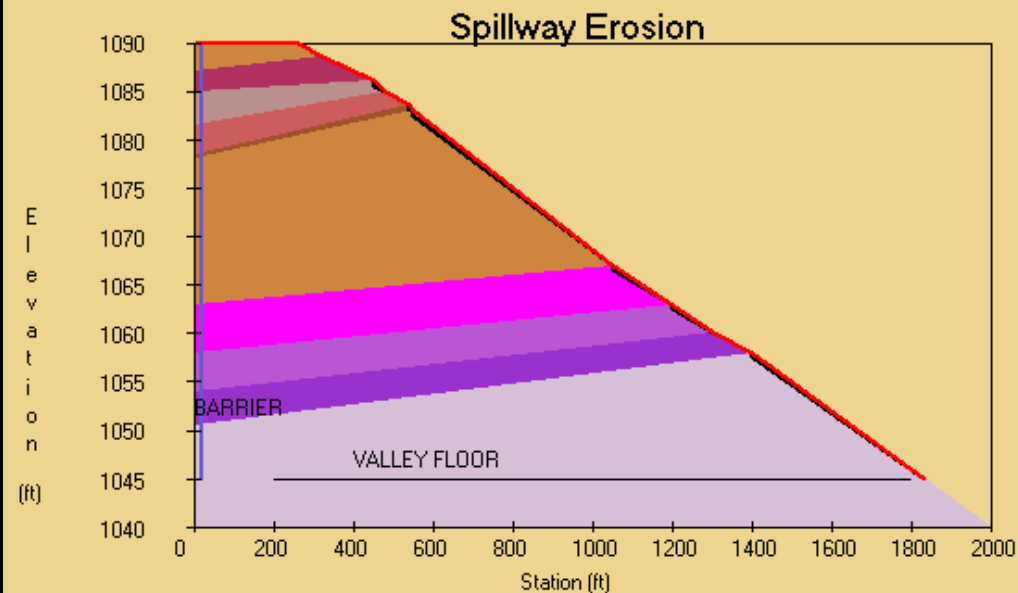
Scarp Heights
up to 24 ft. (7 m.)

Example: Tuttle Creek Spillway



Crest = 1090.0, BW = 600.0, FILE = Tuttle_073_0

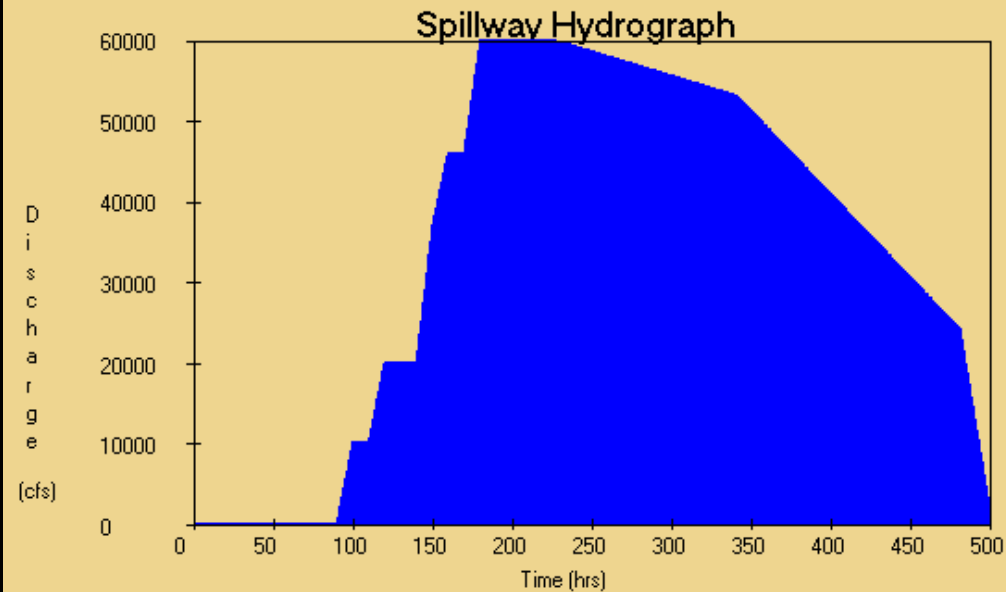
Identifier = Tuttle Creek Spillway



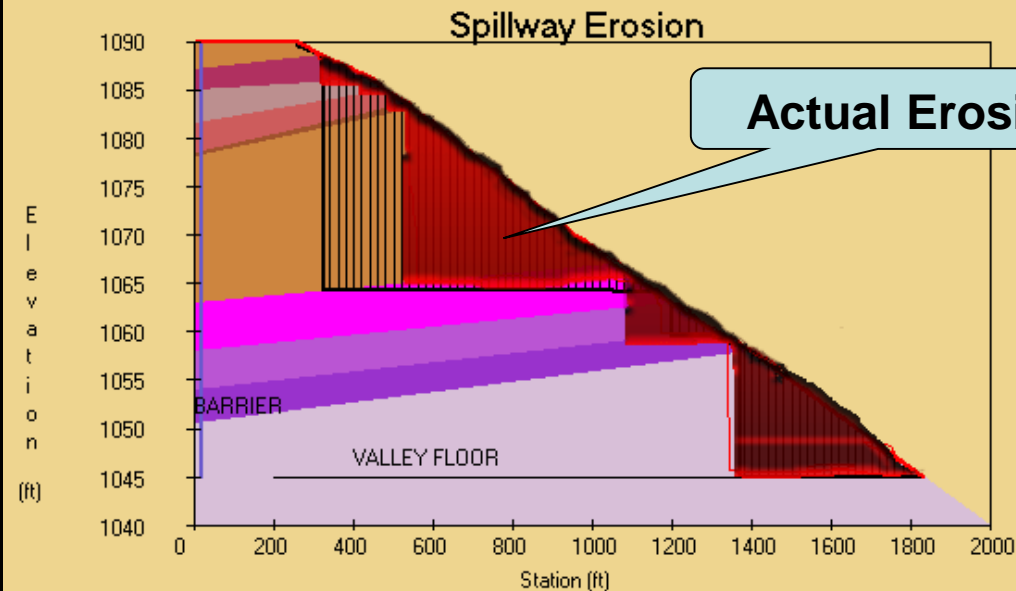
Crest = 1090.0, BW = 600.0, FILE = Tuttle_073_0

Identifier = Tuttle Creek Spillway, Percent Eroded = 0.64, Breach Time = N/A

Example: Tuttle Creek Spillway



Crest = 1090.0, BW = 600.0, FILE = Tuttle_401_0
Identifier = Tuttle Creek Spillway



Crest = 1090.0, BW = 600.0, FILE = Tuttle_401_0
Identifier = Tuttle Creek Spillway, Percent Eroded = 29.19, Breach Time = N/A

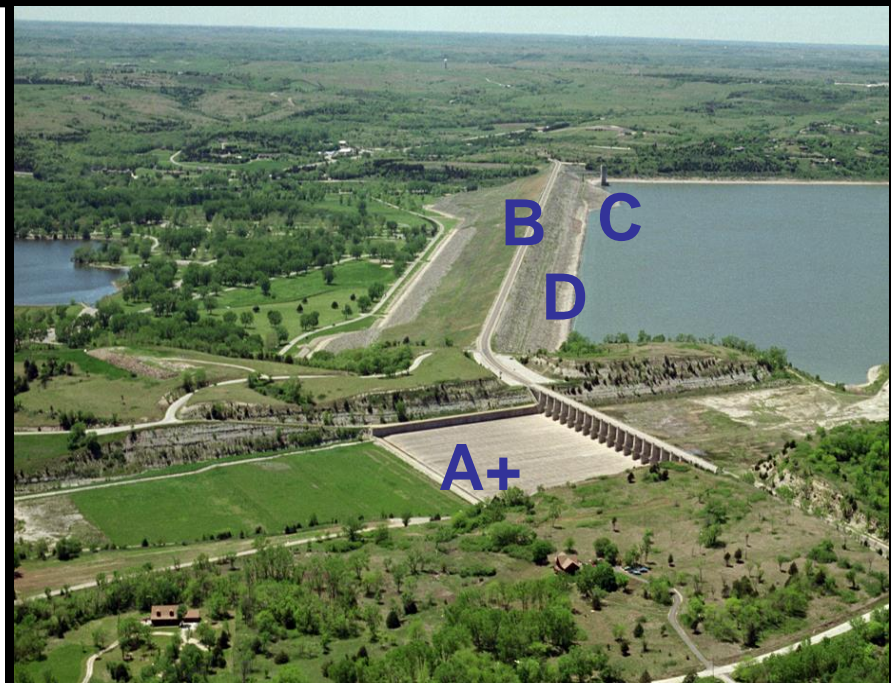
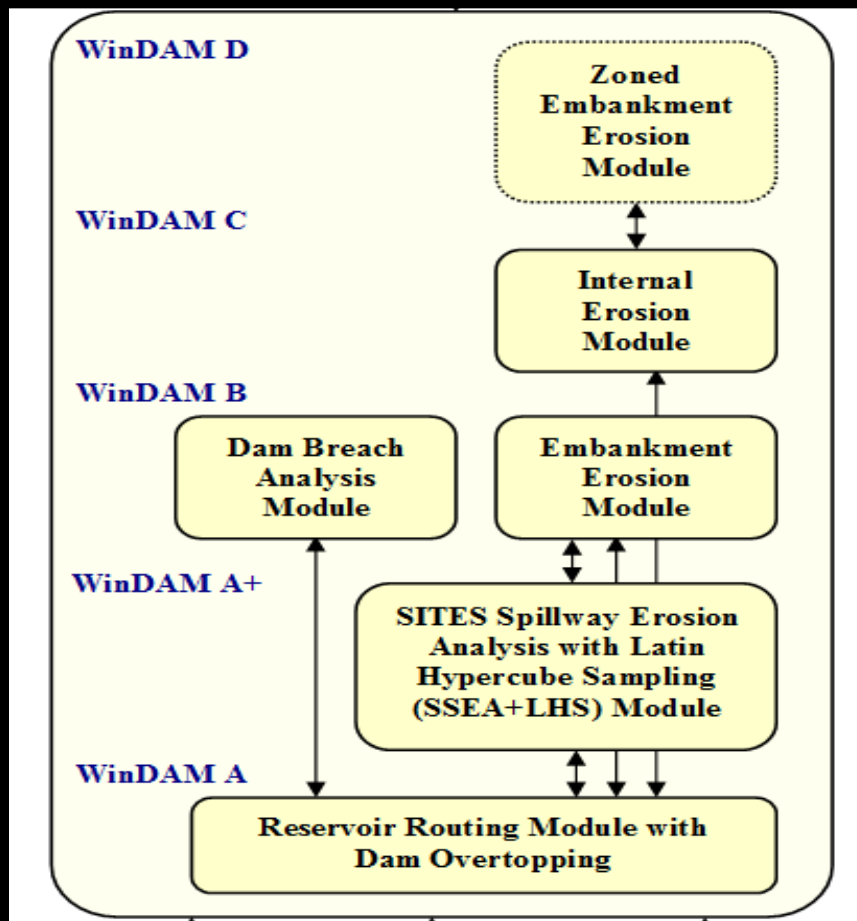
Causes of Dam Failures

Causes of Dam Failures*	Percentage
Dam overtopping and auxiliary spillway failure	23 – 52%
Piping/seepage/internal erosion	25 – 44%
Slides	2 – 15%
Miscellaneous	9 – 40%

* V. Singh, “Dam breach modeling technology”, 1993.

Windows* Dam Analysis Modules (WinDAM)

WinDAM is a modular framework for the design and analysis of water control structures (dams).



Weir Upstream of Test Embankment

USDA Hydraulic Engineering Research Unit (HERU)



Dam Overtopping Breach Analysis

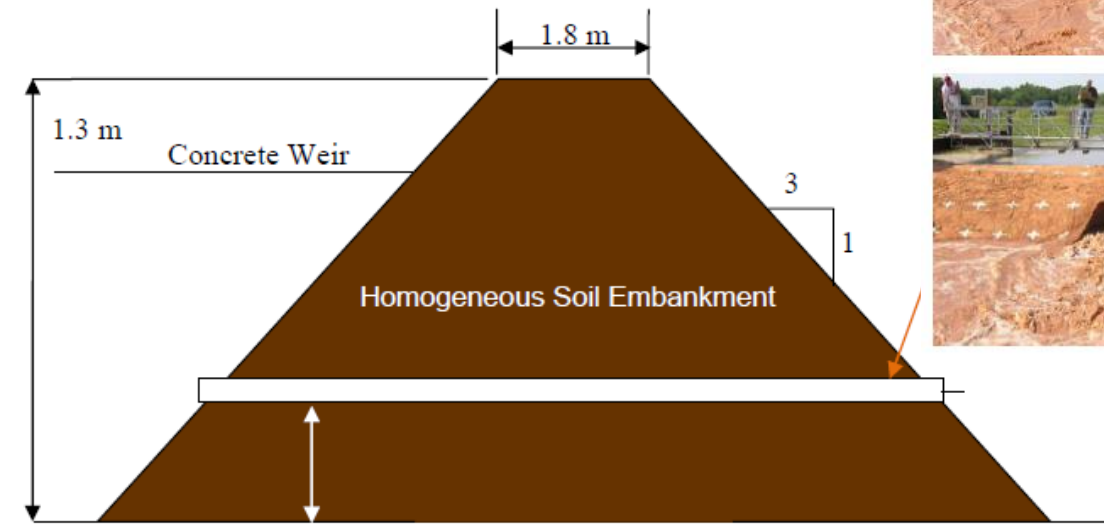


Dam Overtopping Breach Analysis



Internal Erosion Analysis

(weak silty sand material - SM)

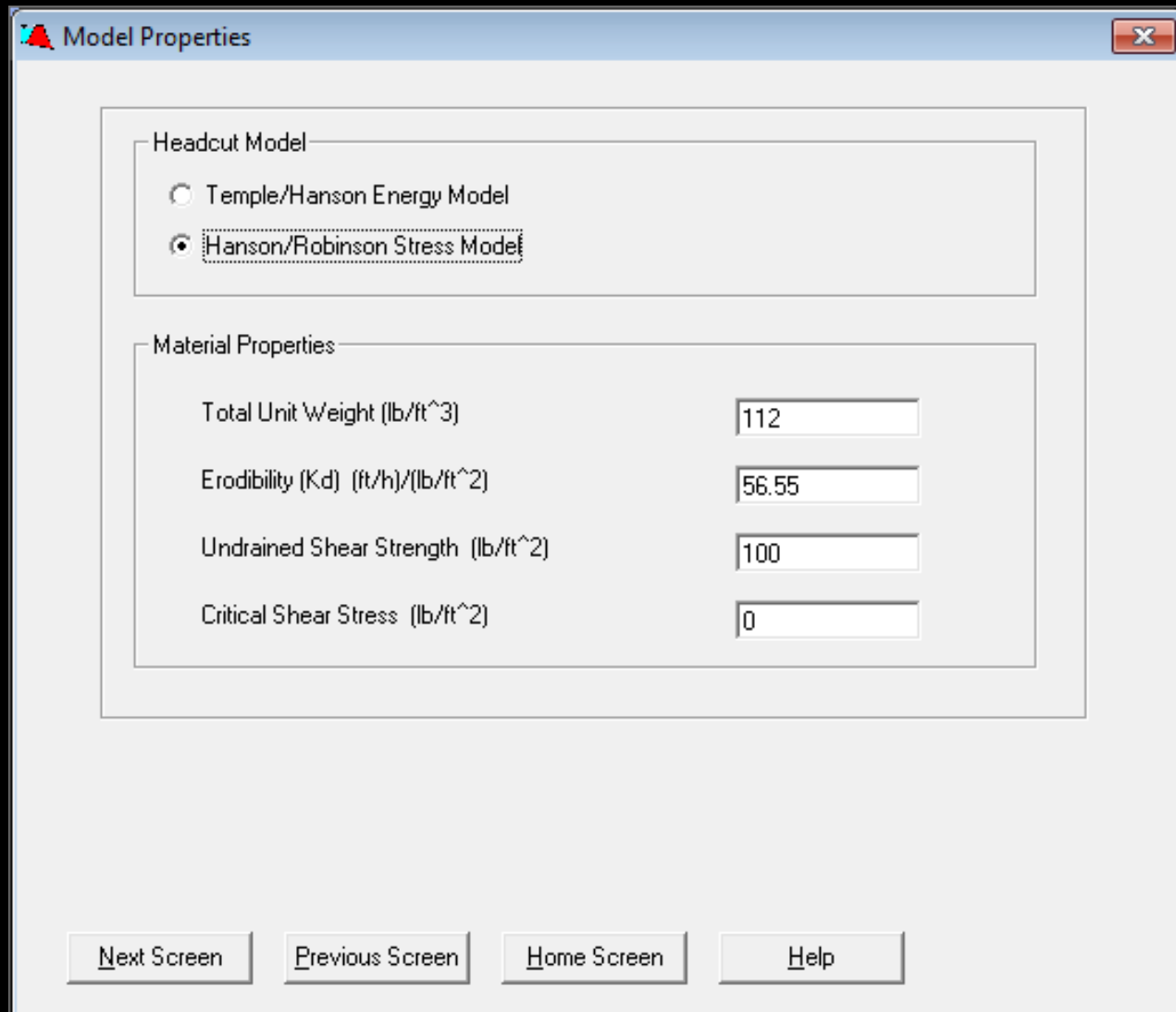


e) 13 min., f) 60 minutes.

$\tau \gg \tau_c$ Rapid Internal Erosion



WinDAM Headcut Model Input



The image shows a screenshot of the 'Model Properties' dialog box in the WinDAM software. The dialog box has a title bar with a close button. It contains two main sections: 'Headcut Model' and 'Material Properties'. In the 'Headcut Model' section, the 'Hanson/Robinson Stress Model' is selected with a radio button. The 'Material Properties' section contains four input fields with their respective units and values: Total Unit Weight (lb/ft³) is 112, Erodibility (K_d) (ft/h)/(lb/ft²) is 56.55, Undrained Shear Strength (lb/ft²) is 100, and Critical Shear Stress (lb/ft²) is 0. At the bottom of the dialog box, there are four buttons: 'Next Screen', 'Previous Screen', 'Home Screen', and 'Help'.

Model Properties

Headcut Model

☐ Temple/Hanson Energy Model

☒ Hanson/Robinson Stress Model

Material Properties

Total Unit Weight (lb/ft³) 112

Erodibility (K_d) (ft/h)/(lb/ft²) 56.55

Undrained Shear Strength (lb/ft²) 100

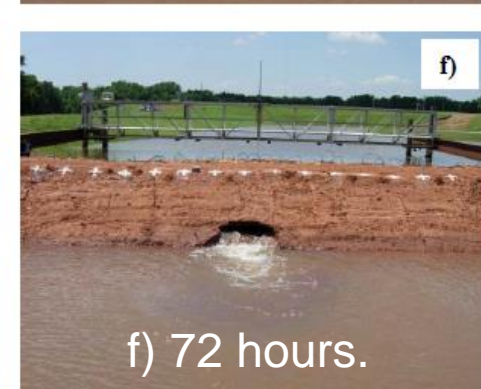
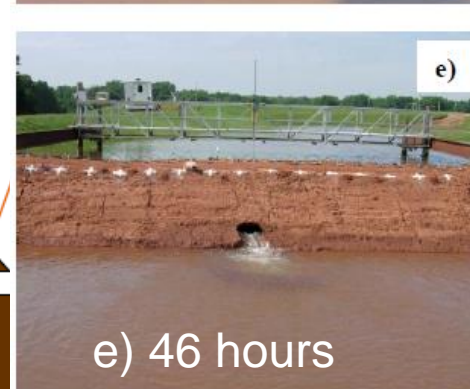
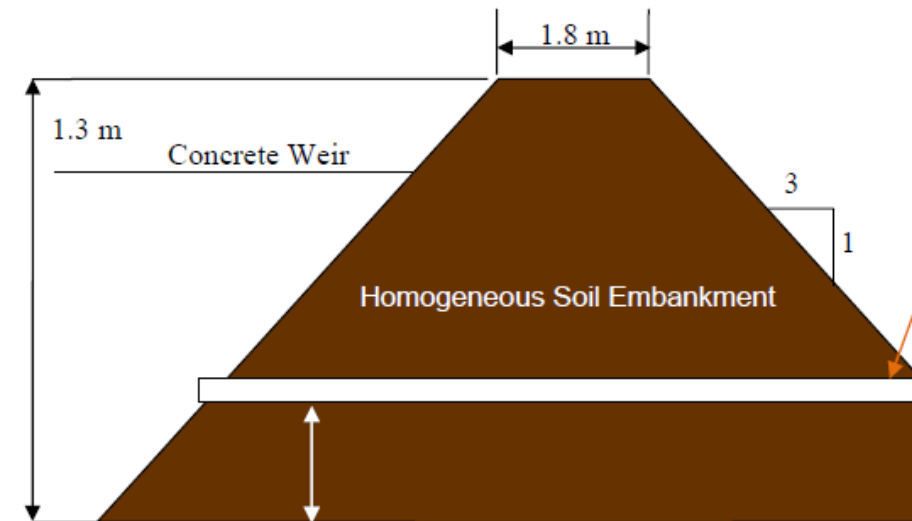
Critical Shear Stress (lb/ft²) 0

Next Screen Previous Screen Home Screen Help

Silty sand (SM) material properties

Internal Erosion Analysis

(stronger clay material - CL)

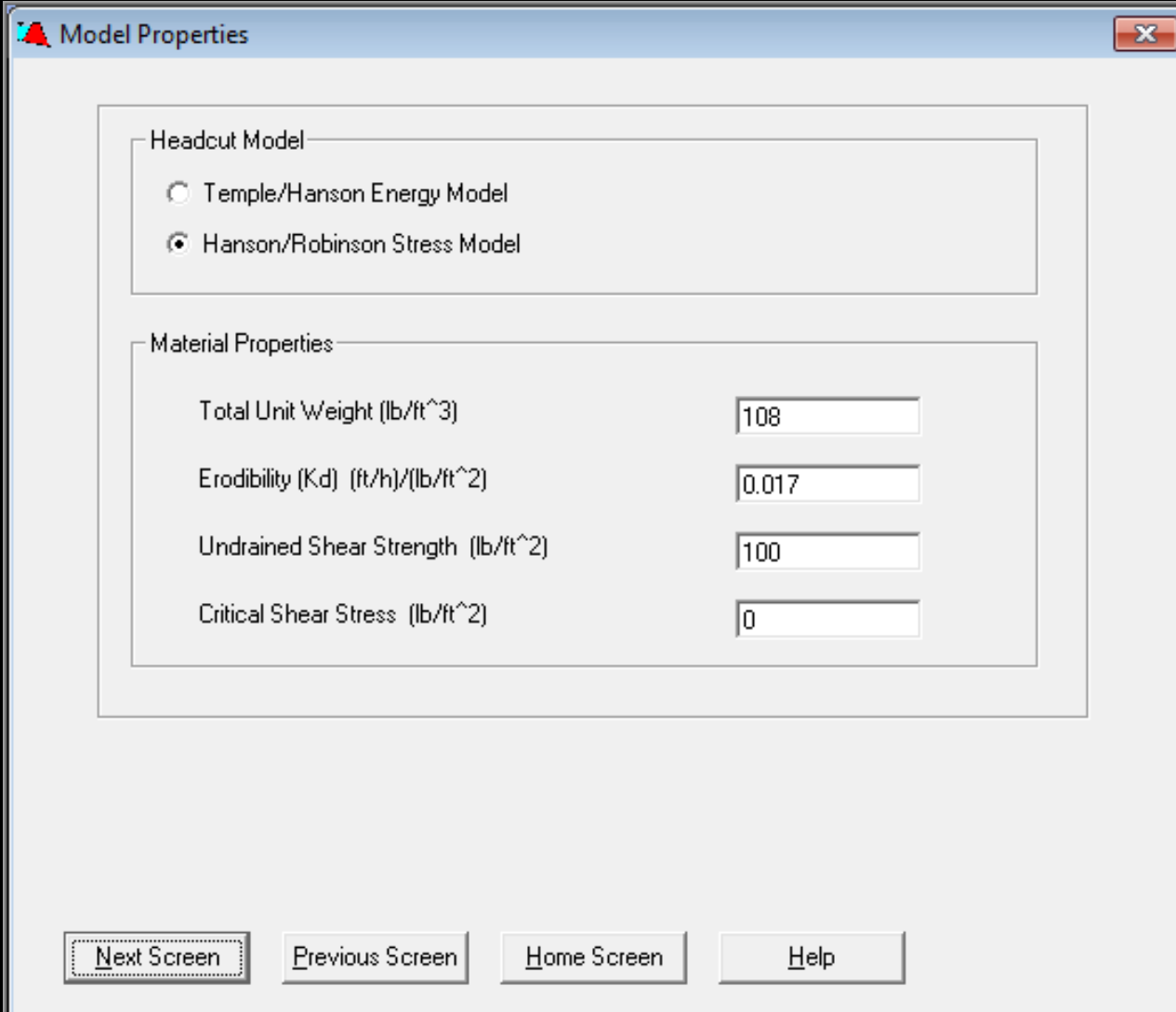


$\tau \sim \tau_c$ Negligible Internal Erosion



$k_d \sim 0.017 \text{ (ft/hr)/psf}$
 $\tau_c \sim 0.0 \text{ psf}$

WinDAM Headcut Model Input



The image shows a screenshot of the 'Model Properties' dialog box in the WinDAM software. The dialog box has a title bar with a standard Windows icon and a close button. It contains two main sections: 'Headcut Model' and 'Material Properties'. In the 'Headcut Model' section, there are two radio buttons: 'Temple/Hanson Energy Model' and 'Hanson/Robinson Stress Model', with the latter being selected. The 'Material Properties' section contains four input fields with their respective units and values: 'Total Unit Weight (lb/ft^3)' with a value of 108, 'Erodibility (Kd) (ft/h)/(lb/ft^2)' with a value of 0.017, 'Undrained Shear Strength (lb/ft^2)' with a value of 100, and 'Critical Shear Stress (lb/ft^2)' with a value of 0. At the bottom of the dialog box, there are four buttons: 'Next Screen', 'Previous Screen', 'Home Screen', and 'Help'.

Model Properties

Headcut Model

☐ Temple/Hanson Energy Model

☒ Hanson/Robinson Stress Model

Material Properties

Total Unit Weight (lb/ft³) 108

Erodibility (Kd) (ft/h)/(lb/ft²) 0.017

Undrained Shear Strength (lb/ft²) 100

Critical Shear Stress (lb/ft²) 0

Next Screen Previous Screen Home Screen Help

Clay (CL) material properties

JET Field test for k_d

- Submerged jet from known orifice diameter
- Measured height above bare soil
- Erosion is measured over time $\rightarrow k_d$



JET Lab Samples



ARS HERU

WinDAM C [Project: c:\workshop]

Model Properties

Headcut Model

☐ Temple/Hanson Energy Model

☒ Hanson/Robinson Stress Model

Material Properties

Total Unit Weight (lb/ft ³)	<input type="text" value="110.0"/>	T_w
Erodibility (K _d) (ft/h)/(lb/ft ²)	<input type="text" value="0.5"/>	K_d
Undrained Shear Strength (lb/ft ²)	<input type="text" value="400.0"/>	U_s
Critical Shear Stress (lb/ft ²)	<input type="text" value="0.008"/>	T_c

Next Screen Previous Screen Home Screen Help


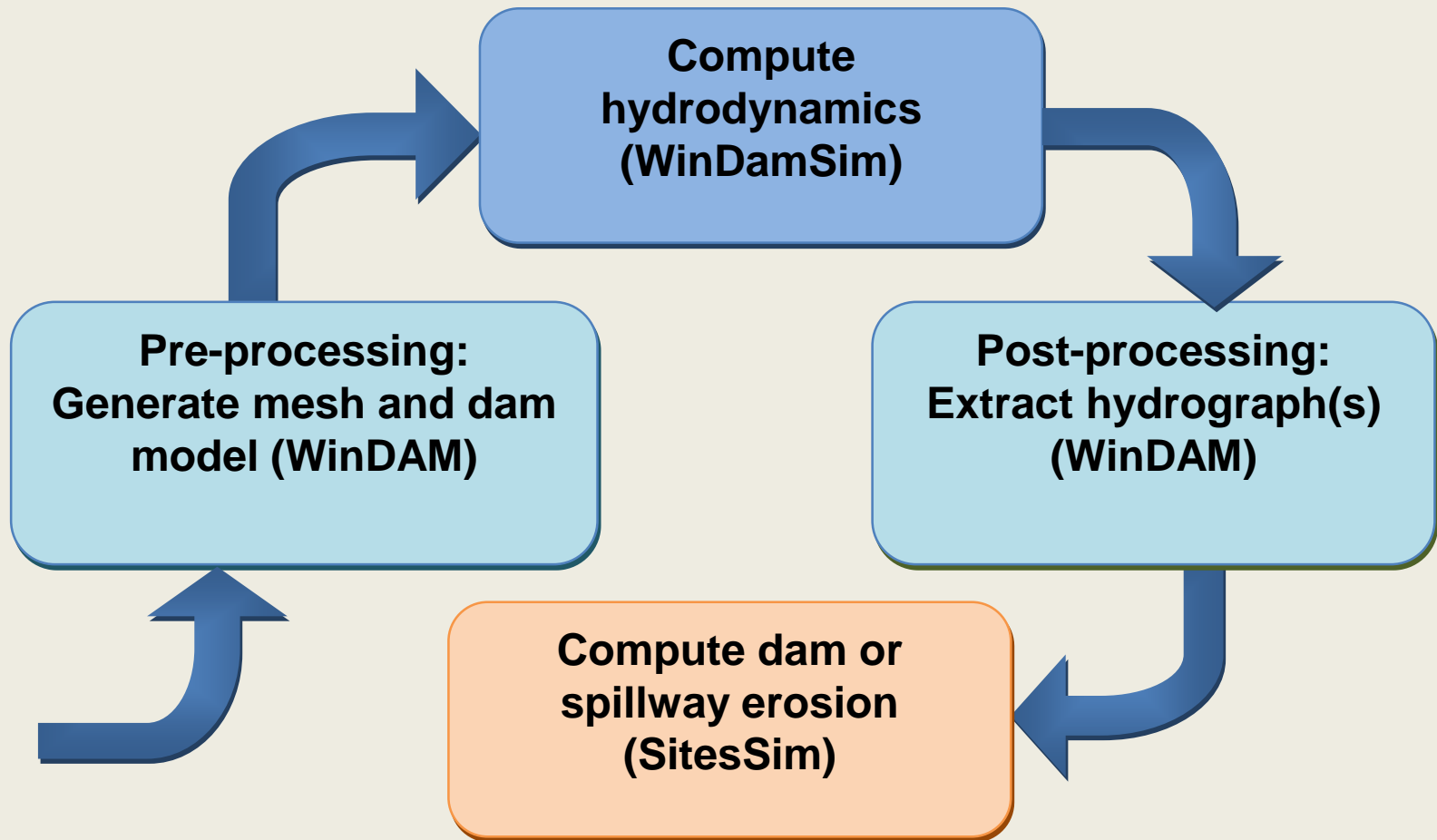


Figure 3. Breach model input

WinDAM Computational Model



Internal Erosion Flow Conditions

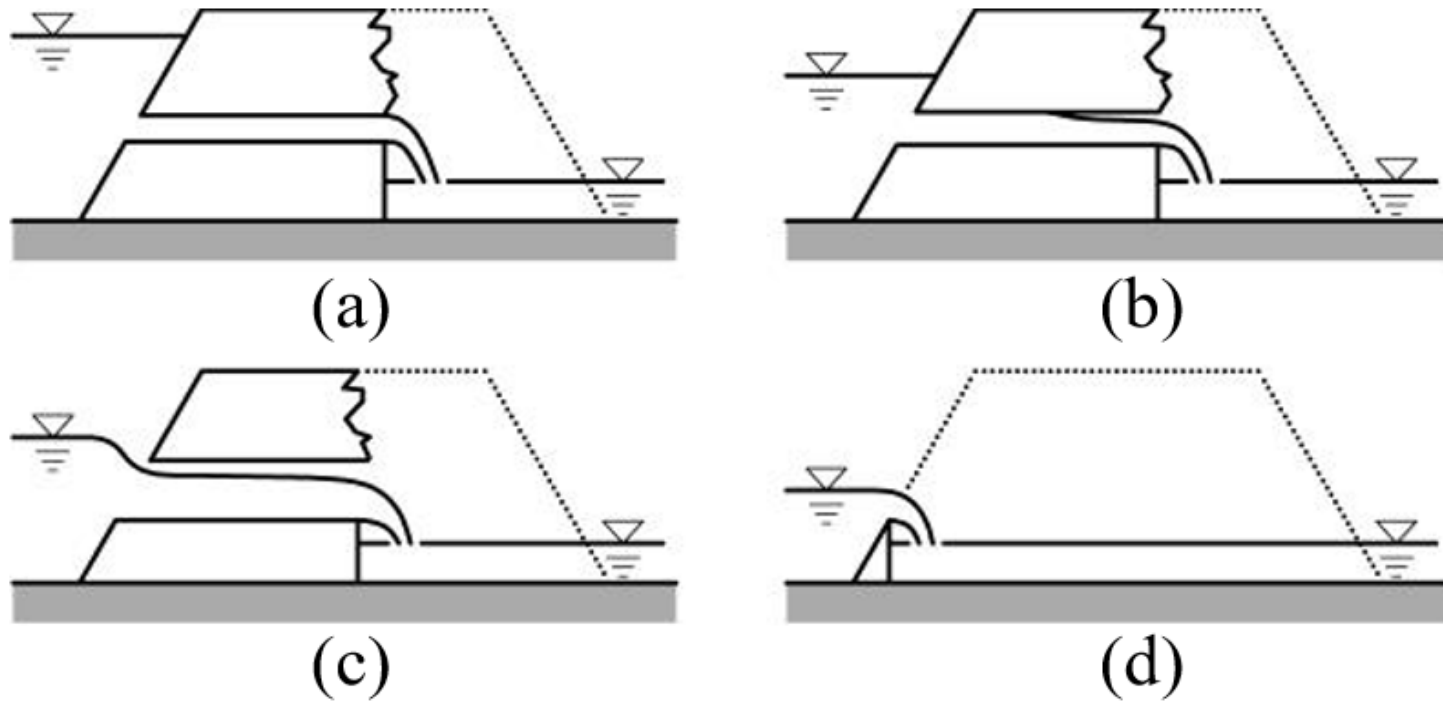
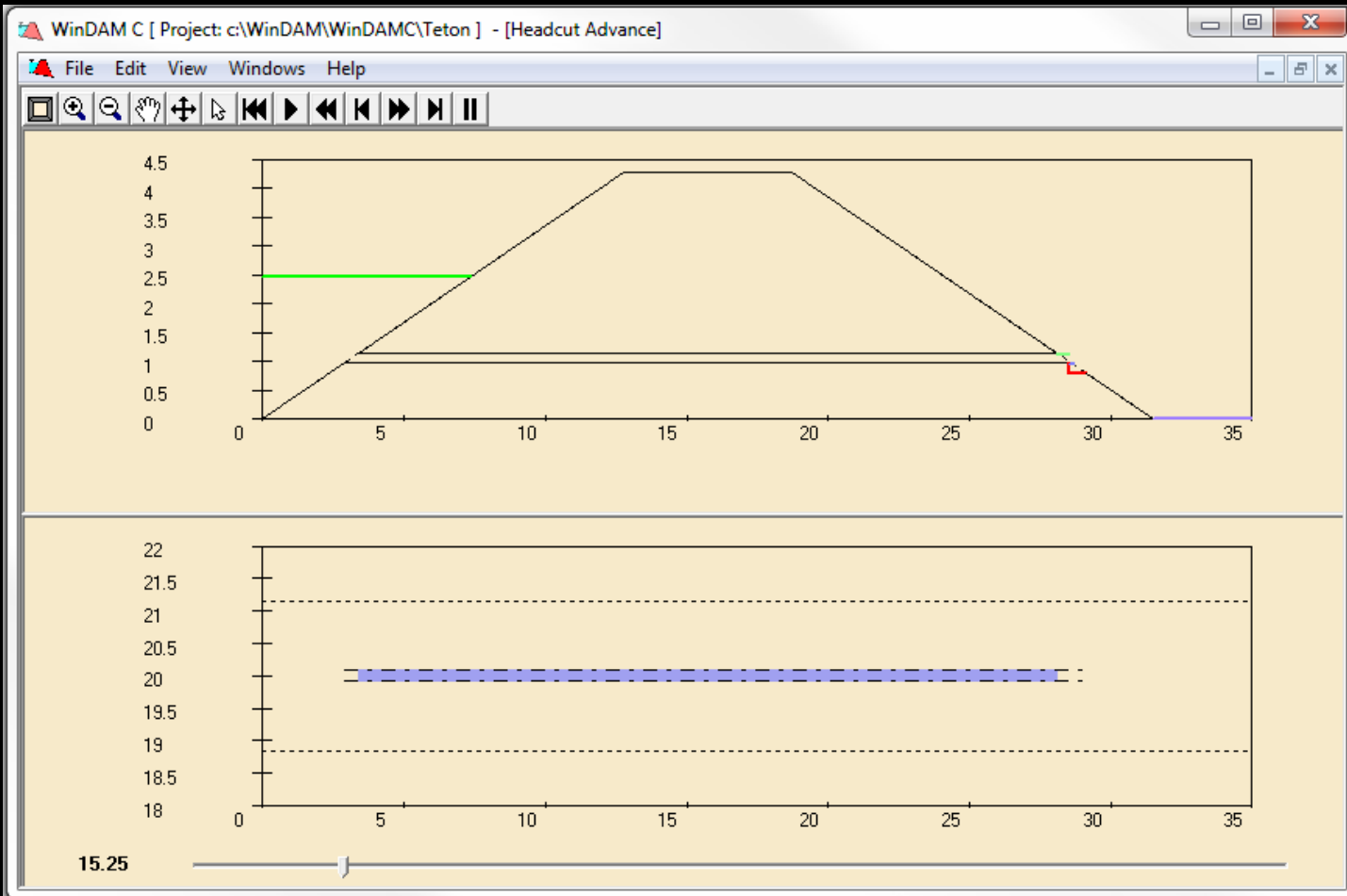
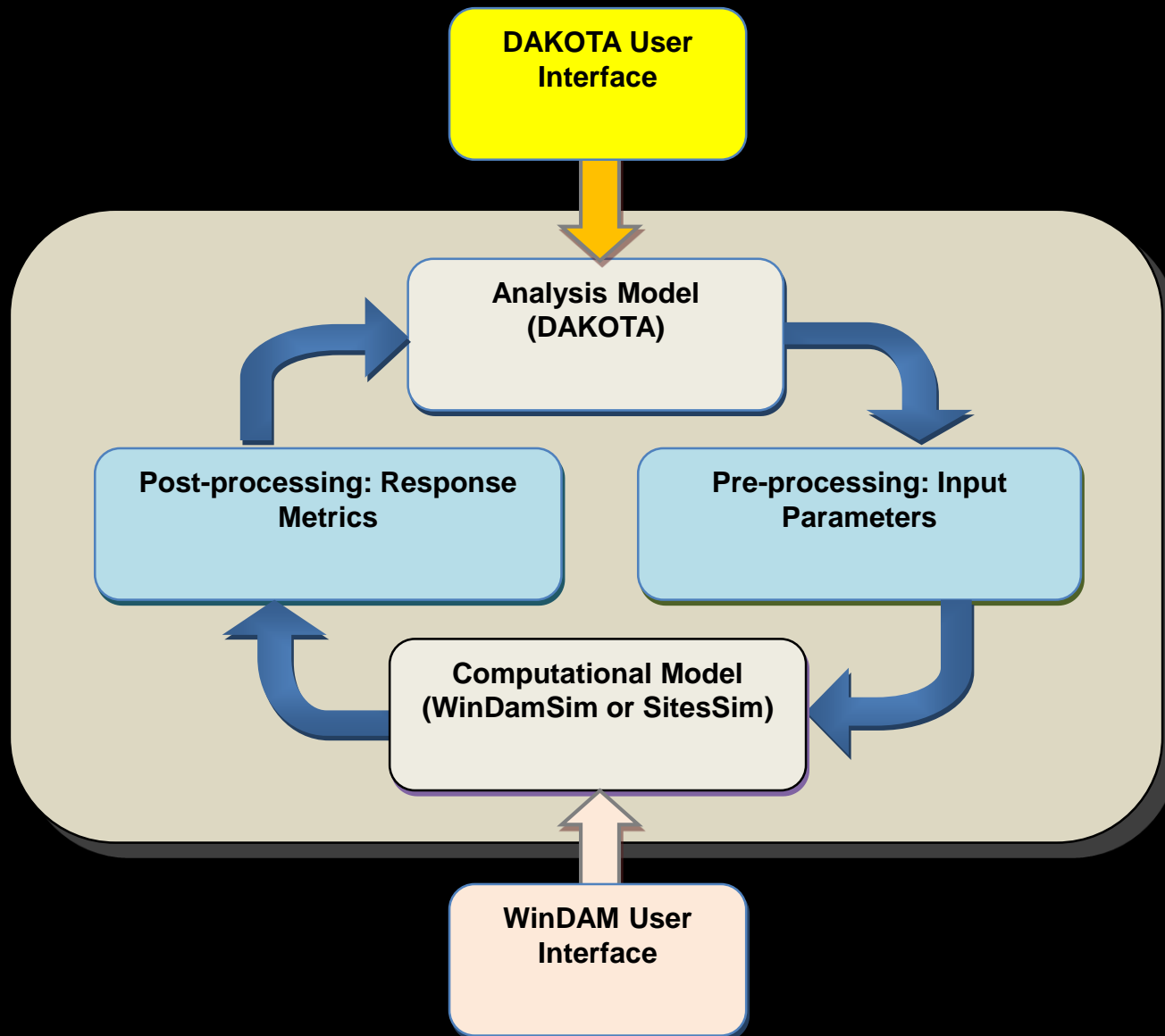


Figure 6. Internal erosion flow conditions

WinDAM Output



Using DAKOTA to drive the Analysis



DAKOTA

- **DAKOTA: Design and Analysis tooKit for Optimization and Terascale Applications** - by Sandia National Laboratories
- DAKOTA adds value to simulation-based analysis:
 - Sensitivity - which input parameters affect performance metrics?
 - Uncertainty (quantification) - how safe, reliable, robust or variable is the system?
 - Optimization - which design performs best?
 - Calibration - which models and parameters best match empirical data?
 - Parameter studies - vary input, how does output change?
- All require **iterative analysis** with the **computational model**.

DAKOTA User Interface

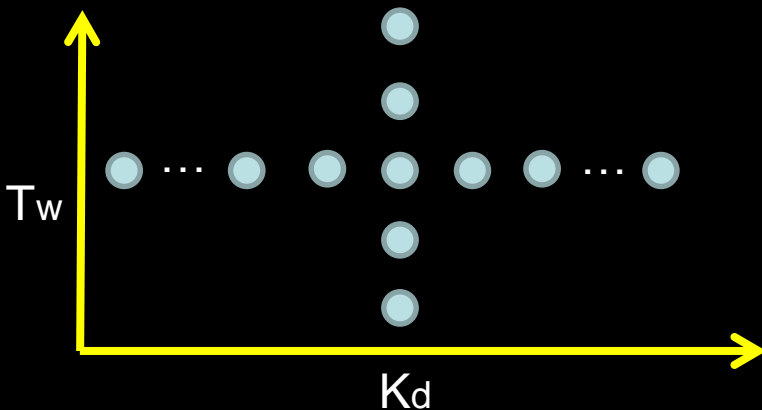
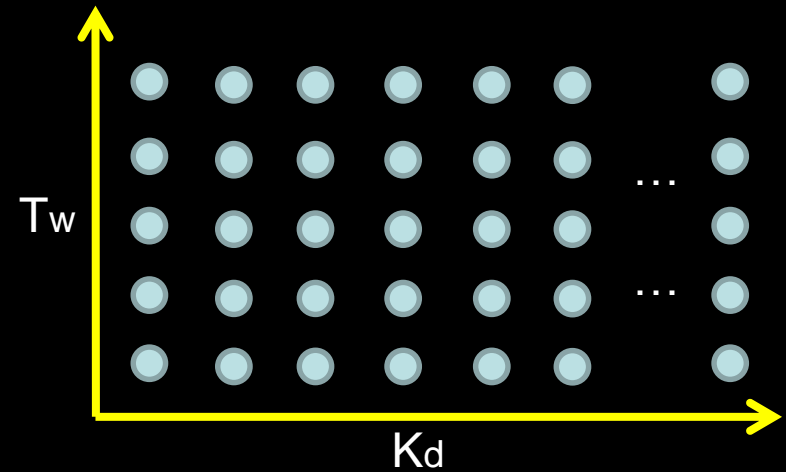
(for parameter studies)

Type of Parameter Study:

☐ Centered Parameter Study ☒ Multi-Dimensional Parameter Study

Type of Properties :

☒ Dam Model Properties ☐ Auxillary Spillway Material Properties



Model Properties :

	Current Value	Lower Bound	Upper Bound	Partitions
Total Unit Weight {TW}:	<input type="text" value="108"/>	<input type="text" value="108"/>	<input type="text" value="112"/>	<input type="text" value="5"/>
Erodibility {Kd} :	<input type="text" value="0.017"/>	<input type="text" value="0.017"/>	<input type="text" value="56.55"/>	<input type="text" value="50"/>
Undrained Shear Strength {US}:	<input type="text" value="100"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>
Critical Shear Stress {CS} :	<input type="text" value="0"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>
Advanced Coefficient {AC} :	<input type="text" value="NA"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>

DAKOTA Input File

```
dakota_windam_multidim.in + (~\...heticInternalErosionExample) - VIM
# DAKOTA INPUT FILE - dakota_windam_multidim.in

environment,
    graphics, tabular_graphics_data
    tabular_graphics_file = 'dakota_multidim.dat'

method,
    multidim_parameter_study
    partitions = 5 50

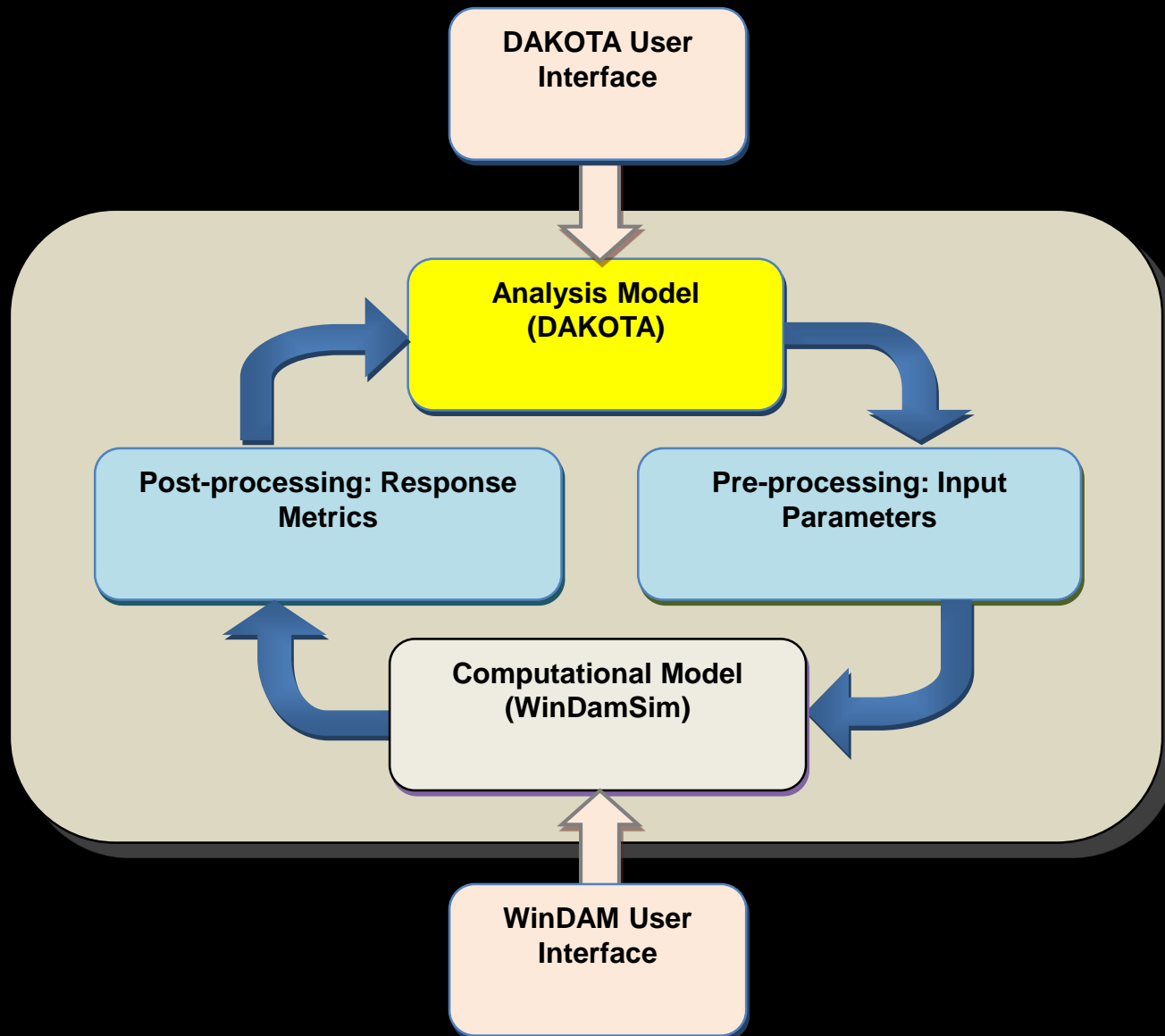
model,
    single

variables,
    continuous_design = 2
    lower_bounds      108      0.017
    upper_bounds      112      56.55
    descriptors        'Tw'     'Kd'

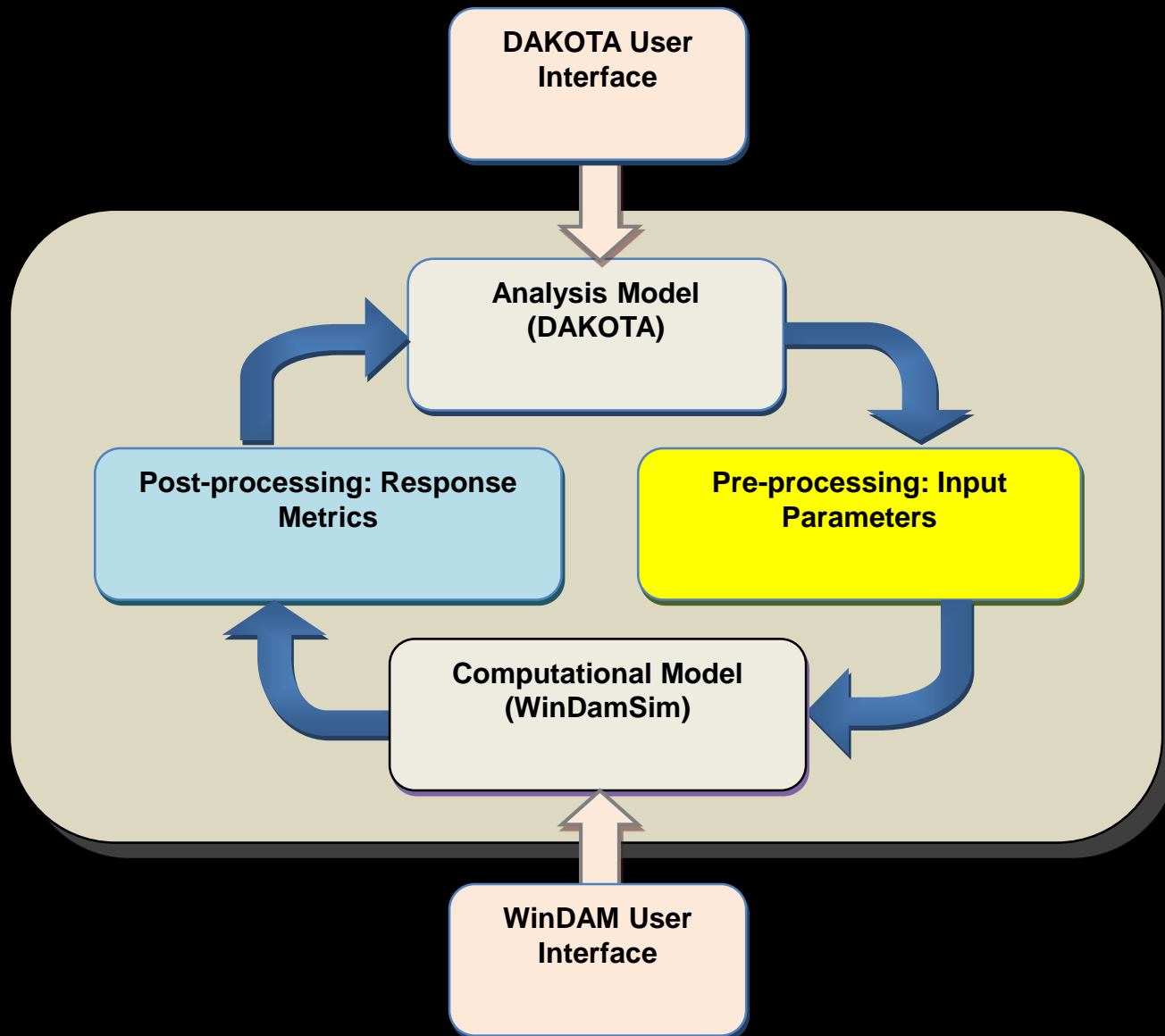
interface,
    system
    analysis_driver = 'winDam.bat'
    parameters_file = 'params.in'
    results_file    = 'results.out'
    file_save

responses,
    num_response_functions = 1
    no_gradients
    no_hessians
```


Using DAKOTA to drive the Analysis



Using DAKOTA to drive the Analysis



DAKOTA Analysis Driver (WinDam.bat)



```
WinDAM.bat (~\Dakota\SyntheticInternalErosionExample) - VIM
perl parseWinDamIn params.in newParams.in
perl dprepro newParams.in example.WDT example.WDC
winDamSim.exe example.WDC
perl parseWinDamOut example.OUT results.out
```

params.in


```
2 variables
1.0800000000000000e+002 Tw
1.7000000000000000e-002 Kd
1 functions
1 ASV_1:response_fn_1
2 derivative_variables
1 DVV_1:Tw
2 DVV_2:Kd
0 analysis_components
1 eval_id
```

parseWinDamIn

newParams.in

```
2 variables
0108.0000 Tw
0000.0170 Kd
```

DAKOTA Analysis Driver (WinDam.bat)



```
WinDAM.bat (~\Dakota\SyntheticInternalErosionExample) - VIM
perl parseWinDamIn params.in newParams.in
perl dprepro newParams.in example.WDT example.WDC
winDamSim.exe example.WDC
perl parseWinDamOut example.OUT results.out
```

example.WDT

example.WDT (~\Dakota\SyntheticInternalErosionExample) - VIM

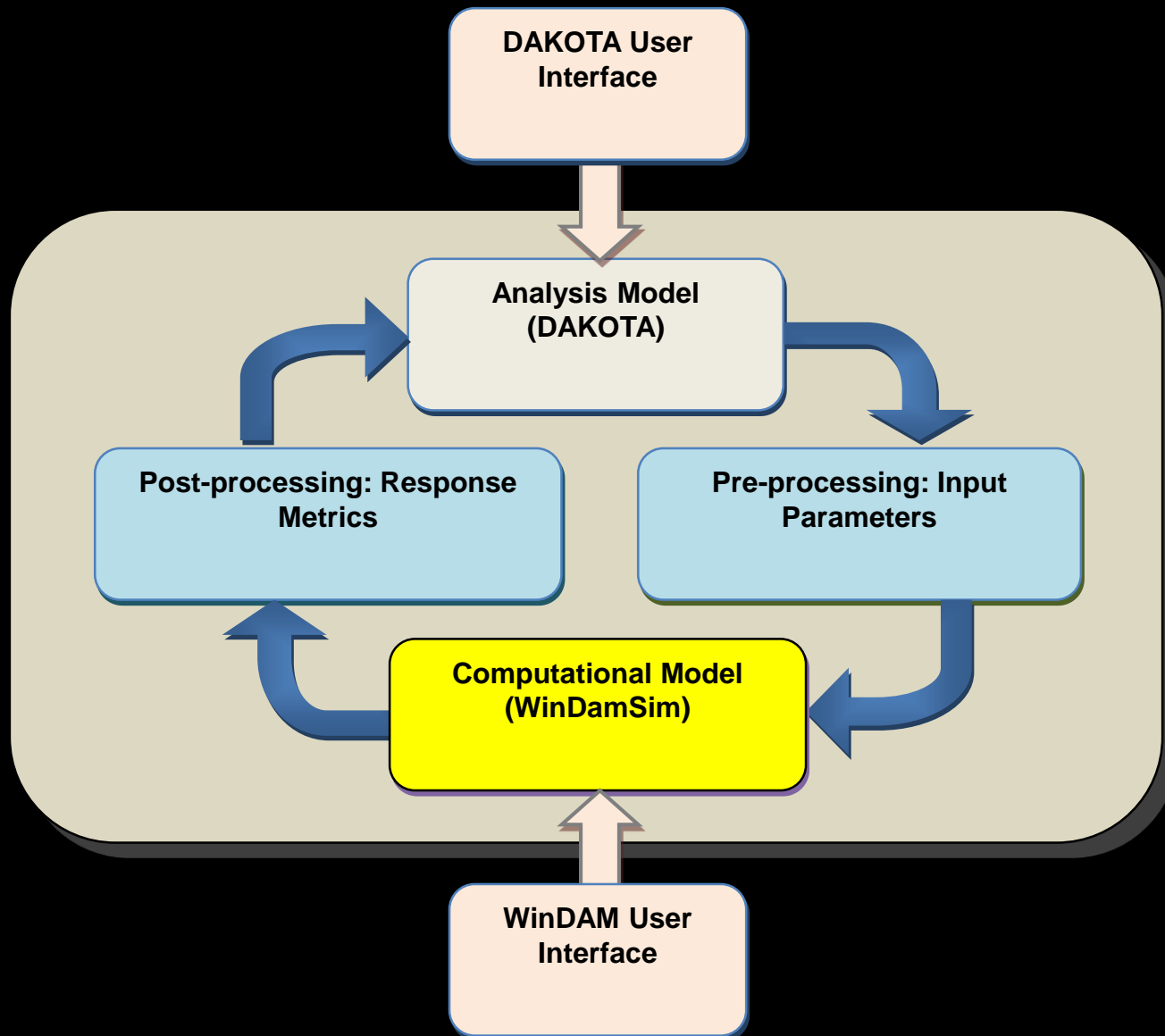
WINDAM	01/01/2009	Internal	Erosion			
OPTION	SIMPLE	EARTH	NOPS	INTERNAL		
+						
IEMODEL	2	{Tw	} {Kd	} 100	0	
HYD	Constant	0.05	0	0C		
		10	10	10	10	10
		10	10	10	10	10
		10	10	10	10	10

example.WDC

dprepro


example.WDC (~\Dakota\SyntheticInternalErosionExample) - VIM									
WINDAM	01/01/2009	Internal	Erosion						
OPTION	SIMPLE	EARTH	NOPS	INTERNAL					
+									
IEMODEL	2	0108.0000	0000.0170	100	0				
HYD	Constant	0.05	0	0C					
		10	10	10	10	10	10		
		10	10	10	10	10	10		
		10	10	10	10	10	10		

Using DAKOTA to drive the Analysis



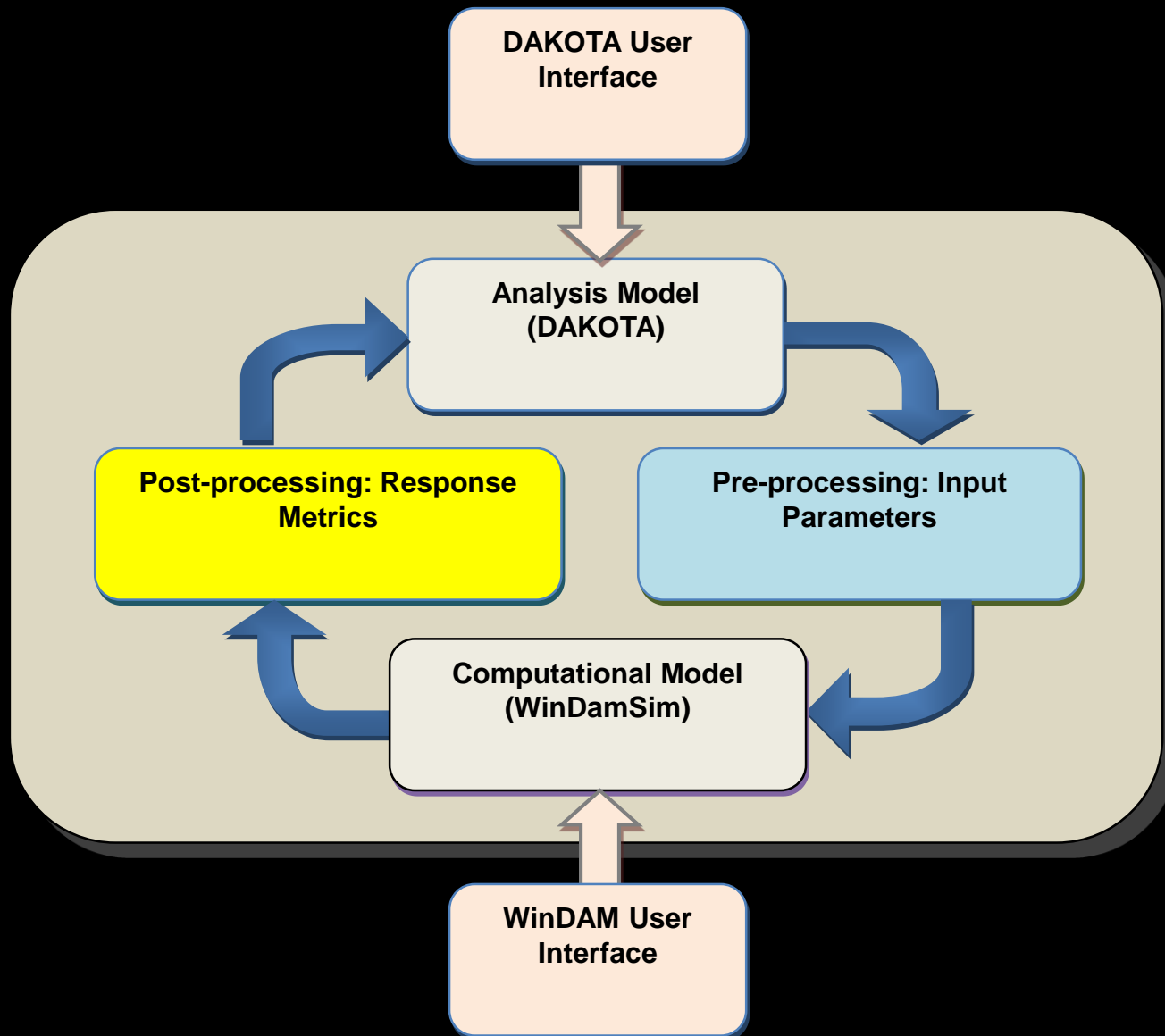
DAKOTA Analysis Driver (WinDam.bat)

WinDAM.bat (~\Dakota\SyntheticInternalErosionExample) - VIM

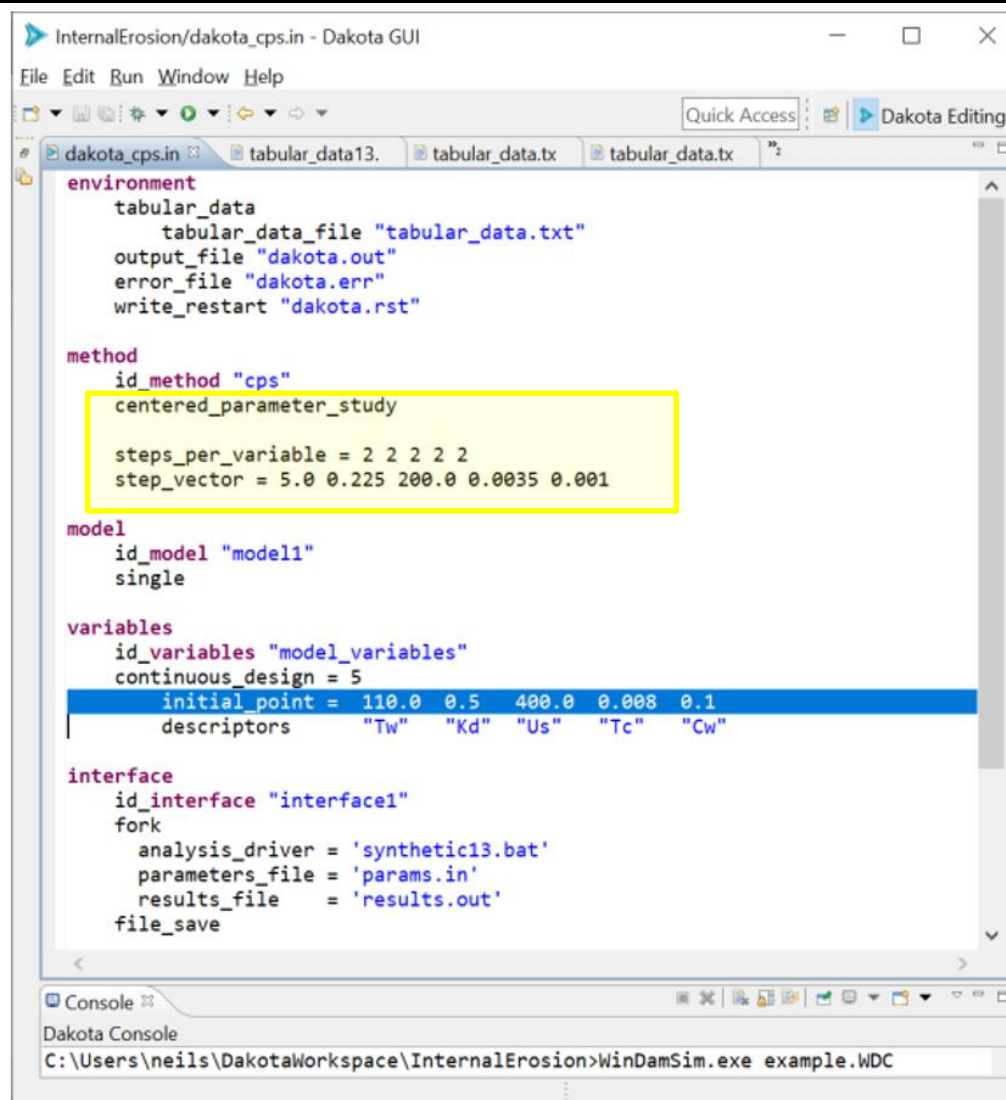


```
perl parseWinDamIn params.in newParams.in  
perl dprepro newParams.in example.WDT example.WDC  
winDamSim.exe example.WDC  
perl parseWinDamOut example.OUT results.out
```

Using DAKOTA to drive the Analysis



Dakota 6.10 Input Format



The screenshot shows the Dakota GUI window titled 'InternalErosion/dakota_cps.in - Dakota GUI'. The main editor displays the input file 'dakota_cps.in' with the following content:

```
environment
  tabular_data
    tabular_data_file "tabular_data.txt"
  output_file "dakota.out"
  error_file "dakota.err"
  write_restart "dakota.rst"

method
  id_method "cps"
  centered_parameter_study

  steps_per_variable = 2 2 2 2 2
  step_vector = 5.0 0.225 200.0 0.0035 0.001

model
  id_model "model1"
  single

variables
  id_variables "model_variables"
  continuous_design = 5
  initial_point = 110.0 0.5 400.0 0.008 0.1
  descriptors "Tw" "Kd" "Us" "Tc" "Cw"

interface
  id_interface "interface1"
  fork
    analysis_driver = 'synthetic13.bat'
    parameters_file = 'params.in'
    results_file = 'results.out'
  file_save
```

The 'method' section, specifically the 'centered_parameter_study' block and its associated parameters, is highlighted with a yellow box. The 'variables' section, specifically the 'initial_point' and 'descriptors' lines, is highlighted with a blue box.

The console at the bottom shows the command: `C:\Users\neils\DakotaWorkspace\InternalErosion>WinDamSim.exe example.WDC`

Figure 14. Dakota centered-parameter study input file

Centered Parameter Study Results

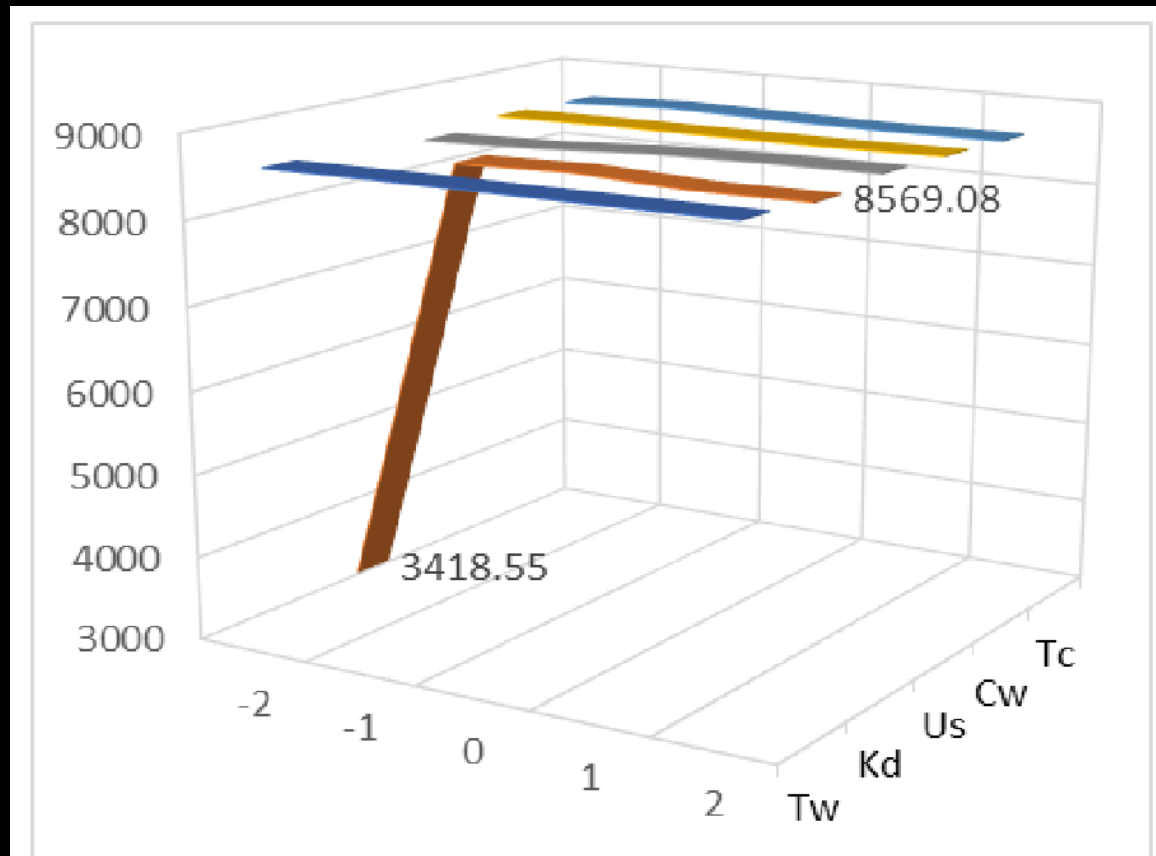


Figure 15. Centered-parameter study results

```
# DAKOTA INPUT FILE
```

```
environment
```

```
  tabular_data
```

```
    tabular_data_file "tabular_data13.txt"
```

```
  output_file "dakota.out"
```

```
  error_file "dakota.err"
```

```
  write_restart "dakota.rst"
```

```
method
```

```
  id_method "method1"
```

```
  sampling
```

```
    sample_type lhs
```

```
    samples = 100
```

```
    variance_based_decomp
```

```
model
```

```
  id_model "model1"
```

```
  single
```

```
variables
```

```
  id_variables "variables1"
```

```
  active all
```

```
  continuous design = 5
```

initial_point	110.0	0.5	400.0	0.008	0.1
lower_bounds	100.0	0.05	100.0	0.0001	0.8
upper_bounds	120.0	5.0	800.0	0.85	1.2
descriptors	"Tw"	"Kd"	"Us"	"Tc"	"Cw"

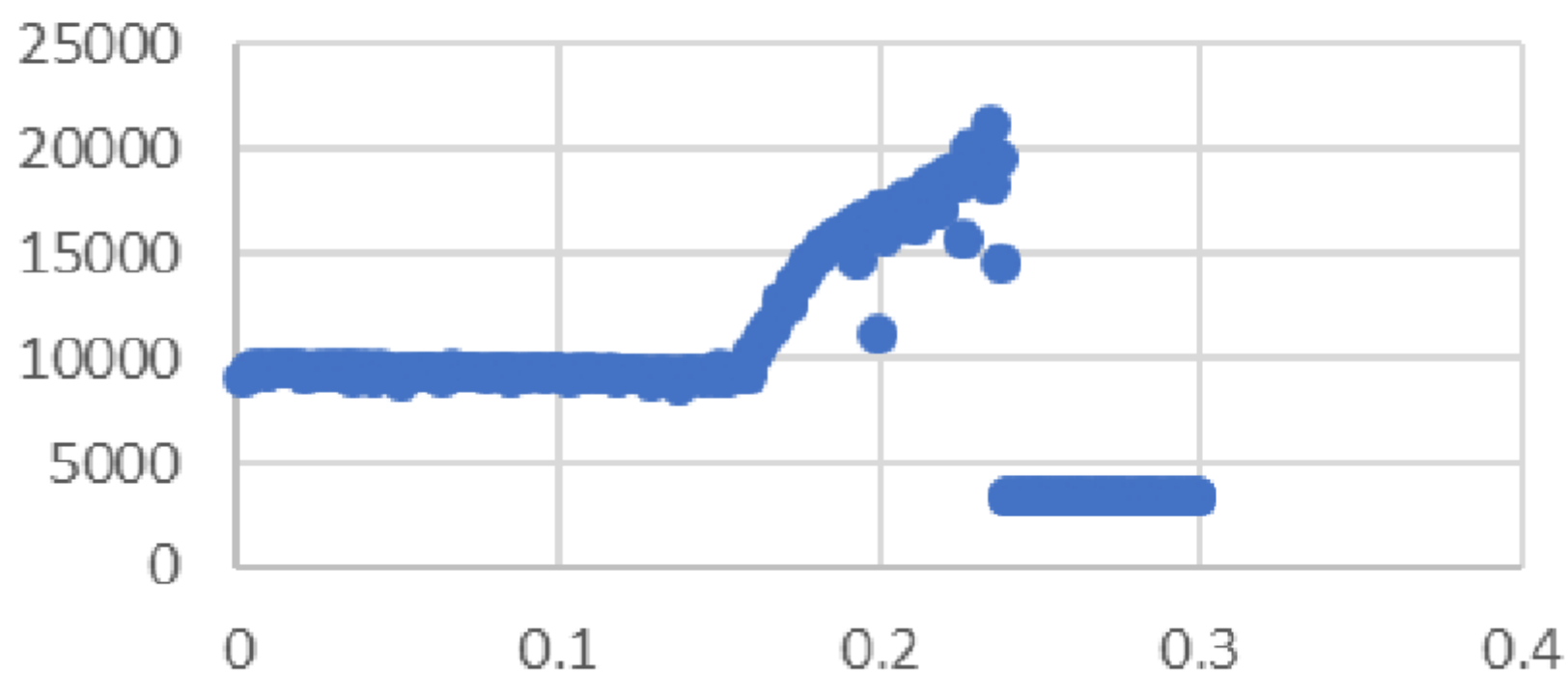
Figure 16. Variance-based decomposition study input

Resulting Sobel Indices

Main	Total	Variable
3.6583120264e-04	6.1933580748e-04	Tw
7.9733886725e-01	8.1438160208e-01	Kd
7.5951019306e-03	2.0226039927e-03	Us
2.8293990703e-01	4.0351278028e-01	Tc
-1.7264200992e-04	2.1209241177e-03	Cw

Figure 17. Sobel indices for peak flow

Tc vs. Max Flow



Summary

- WinDAM
 - Provides a framework to combine existing models and develop new models for dam erosion analysis
- Dakota
 - Provides a framework for parameters studies, uncertainty quantification, and sensitivity analysis
- Together, they provide a powerful framework for dam safety analysis

<http://www.damsafety.info>



Agricultural
Research
Service



Kansas State
University

**WinDAM C (Ver 1.1.9)
Installation Set
(6/28/2019)**

**2011 Hunter Rouse
Hydraulic Engineering
Award Lecture Visuals**

**SITES 2005.1.8 Water
Resource Site Analysis
Software Installation
Set**

**ARS Dam Breach
Research**

**NRCS Hydrology &
Hydraulics**

**NRCS Watershed
Rehabilitation
Information**

**ARS Hydraulic
Engineering Research
Unit**

The United States Department of Agriculture (USDA) and its partners are actively involved in providing the tools and technology for maintaining safe dams. Through the programs of the USDA, Natural Resources Conservation Service (NRCS), USDA has assisted in the construction of over 11,000 dams in 47 states since 1948. These dams provide flood control as well as water supply and recreation opportunities. The USDA, Agricultural Research Service (ARS) works closely with the NRCS to develop the technology needed for the economical design and rehabilitation of these dams. Kansas State University is partnering with the USDA to incorporate the results of research and field experience into computational tools for use in design and maintenance of safe dams. These tools provide the basis for optimal use of natural materials such as vegetation to protect embankments and spillways.

Additional information on the available resources and ongoing research is available by following the links to the left.



Watershed Project Locations



Next Steps

- International Internal Erosion Breach Model Performance Evaluation
 1. EMBREA – HR Wallingford (www.dambreach.org)
 2. WinDAM – USDA, KSU (www.damsafety.info)
 3. AREBA – EDF
 4. DL BREACH – Clarkson University
 5. RUPRO – IRSTEA



Next Steps

Questions?