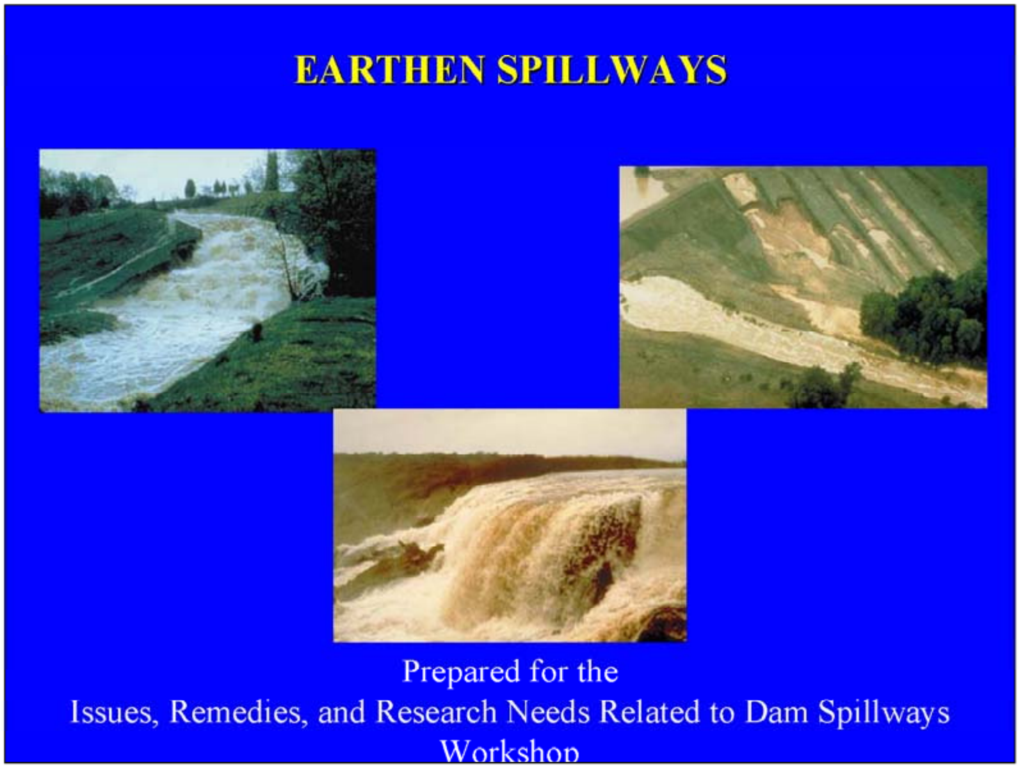
Presentation 5:
Earthen Spillways Design and Analysis
State of the Practice

Thank you. I am with the Agricultural Research Service, and one of the first questions that may come to mind is "What interest does the Agricultural Research Service have in Spillways?"

As the research arm of the USDA, we are responsible for performing the research needed by action agencies; including the Natural Resources Conservation Service. Within USDA, only the Forest Service has its own research branch. Therefore, although we do cooperate with Universities and other Federal agencies, and I'll try to touch on some of their concerns, my discussion today will generally be from the perspective of the USDA.



USDA has significant experience with vegetated earth spillways, and has collected substantial field data from spillway flow events.

The primary concern that is unique to earth spillways is that they are erodible. Or at least we hope that we don't have that problem with other spillways. In general, the philosophy has been that, because flows are infrequent, some erosion may be acceptable providing the spillway is able to pass the design storm without failure.

Because they often offer economic and aesthetic advantages, there have been a large number of earth emergency or auxiliary spillways used. USDA has assisted with the construction of over 10000 flood control reservoirs, and most of these have earth spillways. They have also been used on other dams either alone or in combination with structural components.

They have been designed using various criteria. And I'll touch on that more in just a moment.

As with other types of spillways, the capacity may be inadequate. This may be due to a number of factors, but for USDA assisted dams, the most common reason is a change in hazard classification changing the design storm.

Inadequate maintenance can also create problems. Vegetation and earth are often thought of as not requiring maintenance, but in some instances, maintenance may be an important factor.

EARTH SPILLWAY DESIGN/ANALYSIS
State of the Practice

Historic Approaches

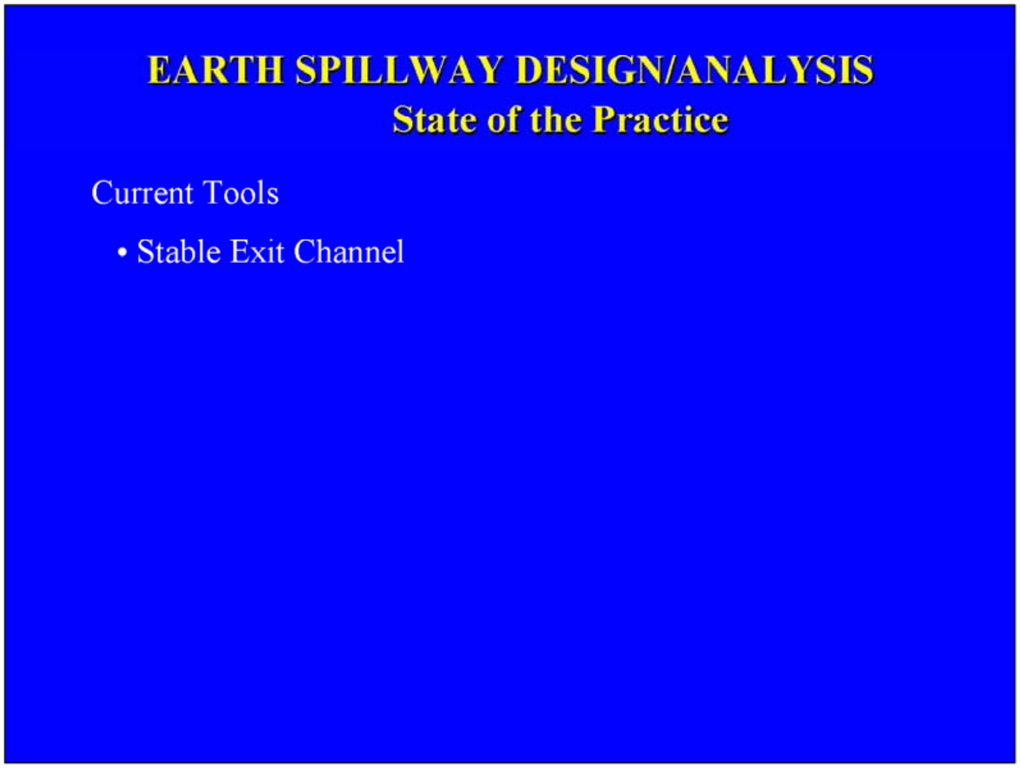
- No Design
- Stable Exit Channel
  Permissible Velocity
  Allowable Stress
  Sediment Transport
- Bulk Length

Looking at the approaches used to design earth spillways during the glory years of dam construction, the first approach was to just let it happen. This approach was generally only associated with smaller agricultural dams in the early years when some engineers tended to be of the opinion that the emergency spillway would never flow anyway and the spillway was just a convenient borrow for the dam construction.

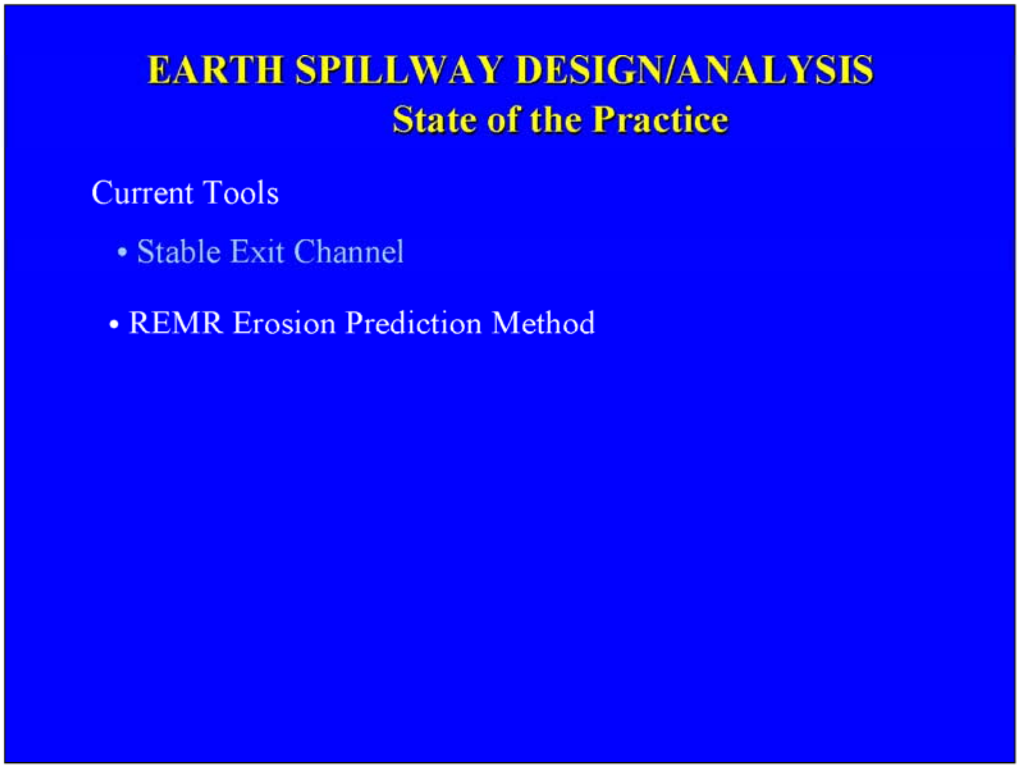
On the other end of the scale was design of the spillway to conduct the design flow as a stable channel. The tools applied were generally the clear water approaches of permissible velocity or allowable stress, but more sophisticated procedures were sometimes used. These procedures were more often applied to larger spillways with longer flow durations. Designing channels using procedures developed for application to canals or stream and river channels tended to be somewhat conservative because of the infrequent and limited duration of spillway flows.

In the 70's the Soil Conservation Service moved to an approach that included both a stable exit channel component and a bulk length, or volume of erosion approach. The exit channel was designed to be stable for an emergency spillway design storm, usually defining the width of the spillway. The concept here was one of the channel not requiring maintenance for less than the emergency spillway storm.

The spillway was also required to have a bulk length determined by the geologic material and the total discharge per unit width of spillway for the freeboard storm. The bulk length was defined as the distance through the crest 2 feet below the hydraulic control.



It may still be appropriate to use channel design and analysis software for spillway design or evaluation. This is particularly true when long exit channels are involved and sediment transport is expected to be a major consideration.



Other tools have also been developed, including the REMR erosion prediction method developed by the Corps.

REMR RISK CLASSES

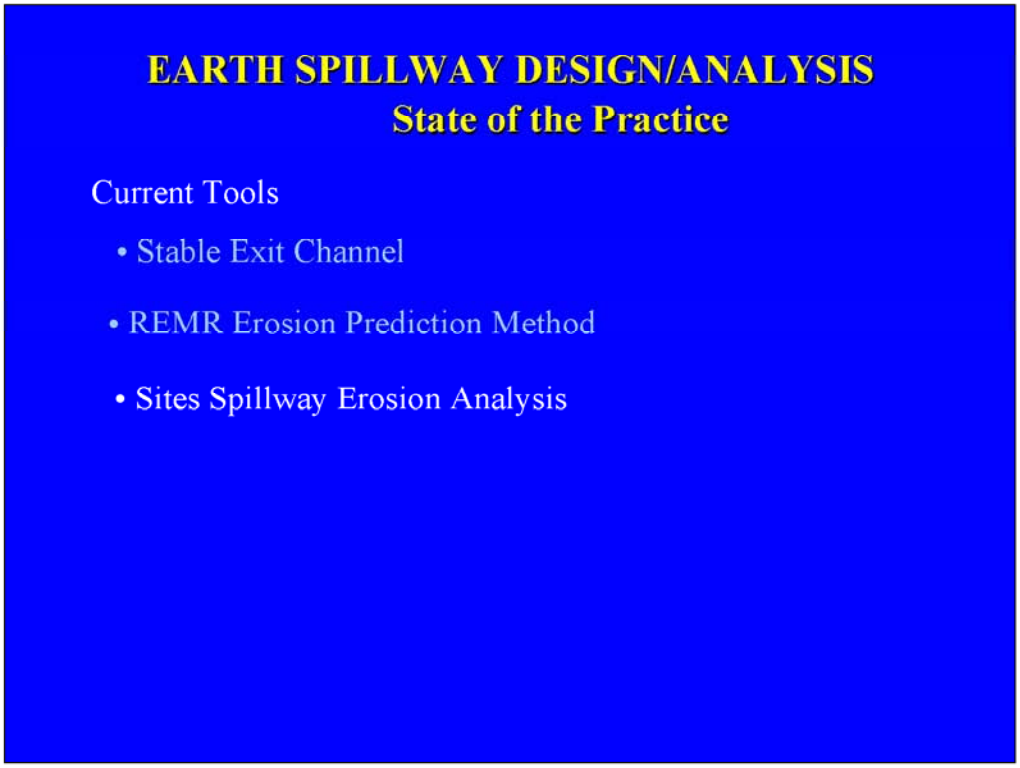
EROSION RISK	EROSION RISK CLASS			
	AAAA	AAA	AA	A
Slope (percent)	30 - 45	15 - 30	4 - 15	< 4
Flow Velocity (m/sec)	3.1 – 4.6	2.1 – 3.1	1.2 – 2.1	< 1.2
Geometric Anomaly	Extreme	Major	Moderate	None
AAAA	High Erosion Risk			
AAA	Significant Erosion Risk			
AA	Moderate Erosion Rate			
A	Slight Erosion Rate			

This empirical method is based on a combination of experience and judgment that compares an erosion risk class that includes hydraulic attack in the form of maximum mean velocity, against

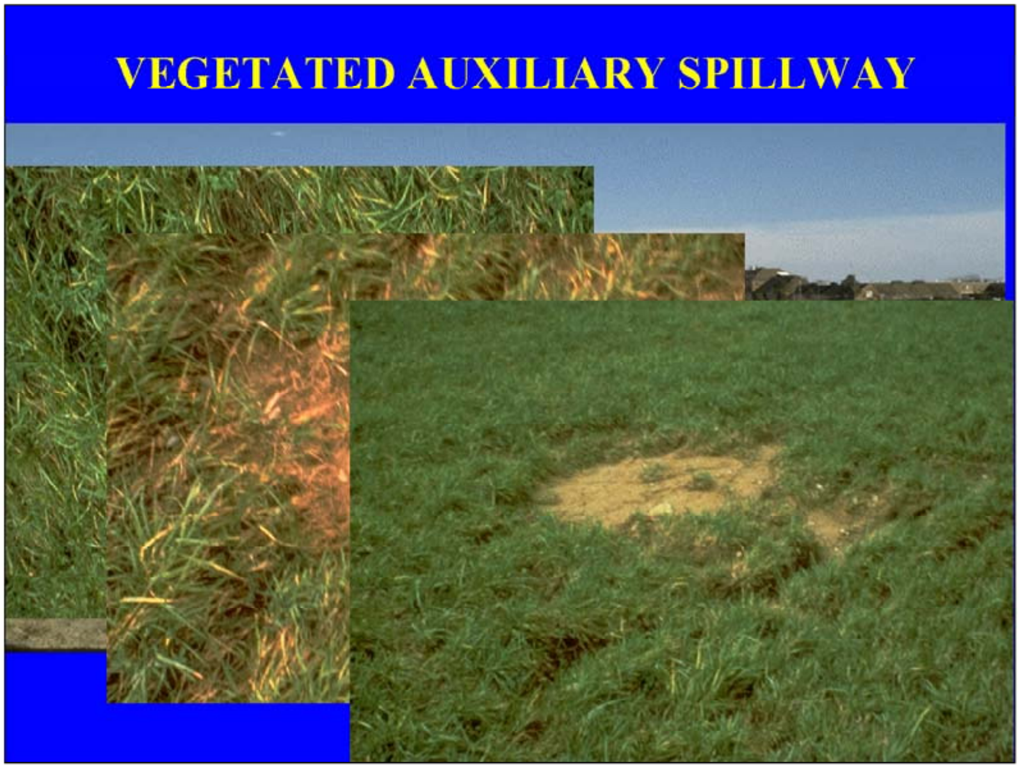
REMR EROSION POTENTIAL CLASSES

EROSION POTENTIAL	EROSION POTENTIAL CLASS			
	AAAA	AAA	AA	A
AAAA	Erosion Resistant Rock			
AAA	Moderately Erosion Resistant Rock			
AA	Moderately Erodible Material			
A	Erodible Soil			
LITHOLOGY				
Sandstone	xxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxx			
Shale & Siltstone	xxx xxxxxxxxxxxxxxxxxxxxxxxx			
Limestone	xxxxxxxxxxxxx			
Granular Soil (Low PI)				xxxxxx xxxxx
Cohesive Soil (High PI)			xxxxxxxxxxxxxx	
Intrusive Igneous	xxxxxxxxxxxxx			
Extrusive Igneous	xxxxxxxxxxxxxxxxxxxxxxxxxxx xx			
Massive Metamorphic	xxxxxxxxxxxxxxxxx xx			
Foliated Metamorphic	xxxxxxxxxxxxxxxxxxxxx			
SUBSTANCE				
Density (kg/m^3)	> 2243	2003 - 2243	1858 - 2003	< 1858
Uniaxial Strength (MPa)	> 41.4	13.8 – 41.4	1.3 – 13.8	< 1.0

Erosion potential classes. Note that here, the table has been truncated, there is more geologic information required than shown; and that the focus tends to be on rock materials. If the erosion risk is greater than the potential, then damage is expected.

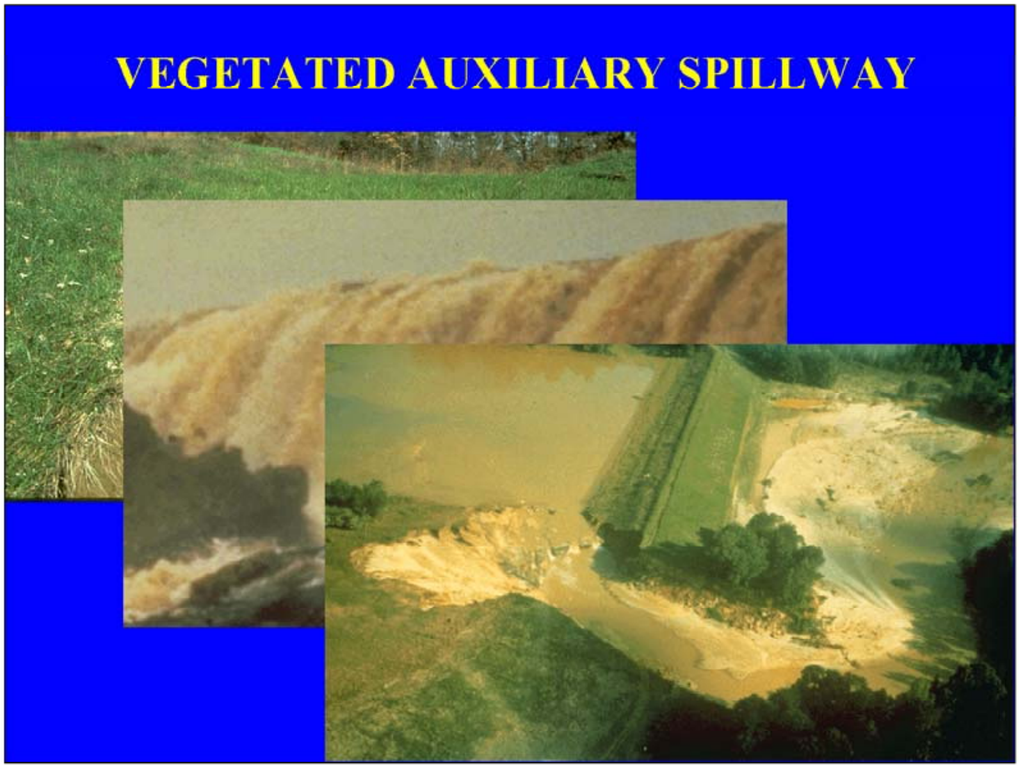


The approach that is presently used by USDA's NRCS for design and analysis of earth spillways is that incorporated into the Sites software. I'll take a few minutes to go into the basis for this procedure, and then address some of its limitations as we move into the research needs.



The Sites software uses a three phase spillway erosion model to evaluate the potential for spillway breach. The beginning point for the conceptual model is a spillway such as we see in the background. For this condition, the erodible boundary is initially protected from erosion by the presence of the grass cover. However, if the flow persists long enough or the stress is high enough, erosion will be initiated in a weak area (Natural materials such as vegetation and soil are never homogenious), and the cover will begin to unravel. The weak area will enlarge until the vegetal cover is no longer effective and the flow tends to concentrate in the local eroding area. That local removal is phase 1 of the failure process.

Phase 2 of the process consists of enlargement and deeping of the eroding area due surface detachment as a result of the flow and stress concentrations. The end of this phase is the point where the flow tends to break up, and a headcut is formed. The depth of erosion corresponding to the end of phase 2 is discharge dependent.



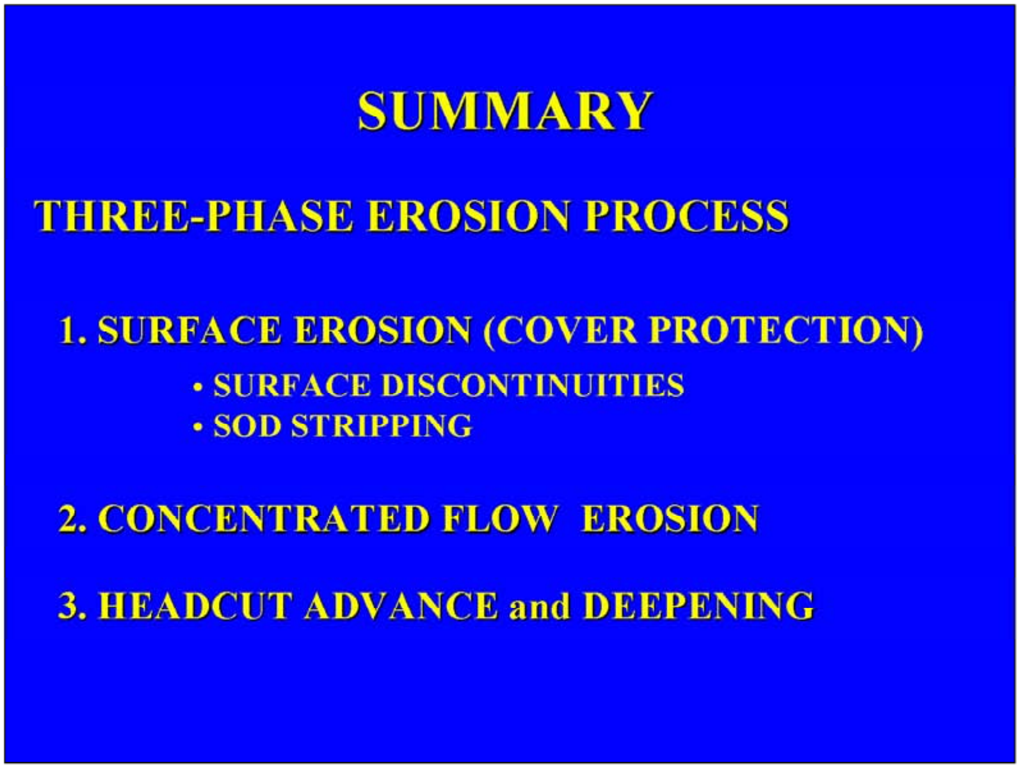
The third phase of the failure process is the deepening and upstream movement of the headcut. Widening occurs simultaneously, but is not tracked by the present Sites computations.

For worst case conditions, the upstream advance of the headcut may result in spillway breach and drainage of the reservoir. However, the Sites model was developed only to evaluate potential for breach, and does not take the computations on through the actual breach process. We're working on that for embankments and consider the development of that phase of the model to be a research need.

Another thing that is introduced in the sites model is the concept of major and minor discontinuities in the vegetal cover. These can be very important for spillways designed for low head conditions in highly erodible materials. Minor discontinuities are those such as cross-roads, or trees;

Major discontinuities such as access roads immediately concentrate the flow and essentially negate phase 1 protection.

Note also, that for large heads and steep exit channel slopes, phase 1 protection may not be significant anyway.

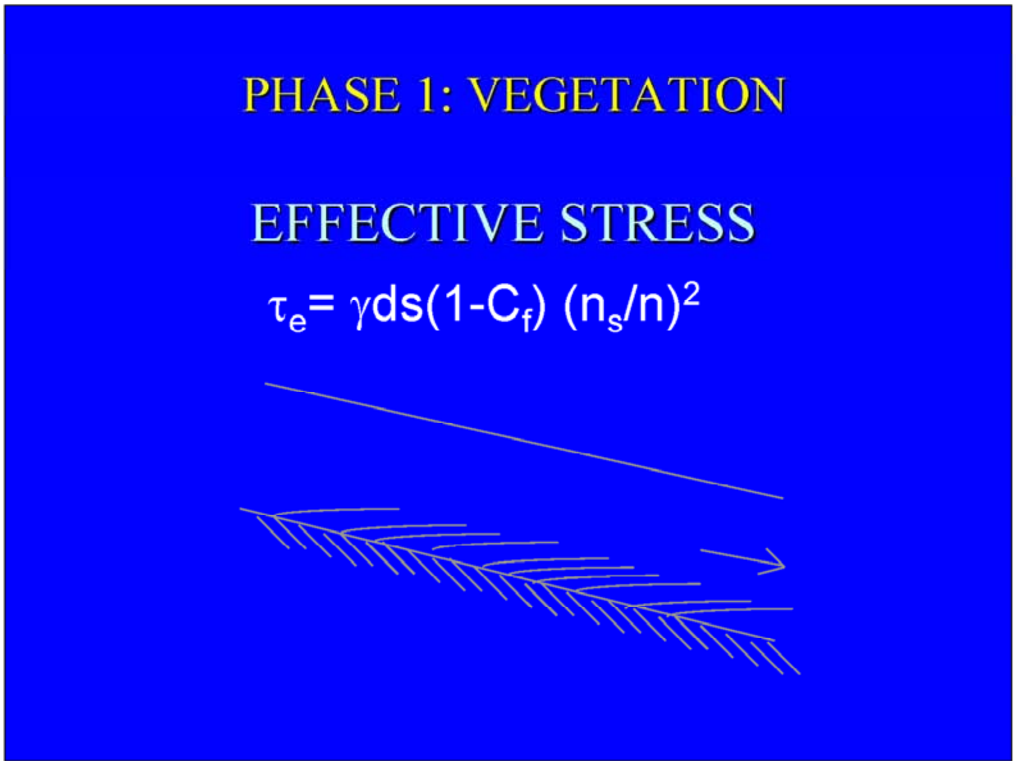


Briefly then, the Sites model describes a three-phase process of surface cover failure, including accounting for discontinuities. We also account for stripping of shallow rooted covers, although I didn't cover that for reasons of time today.

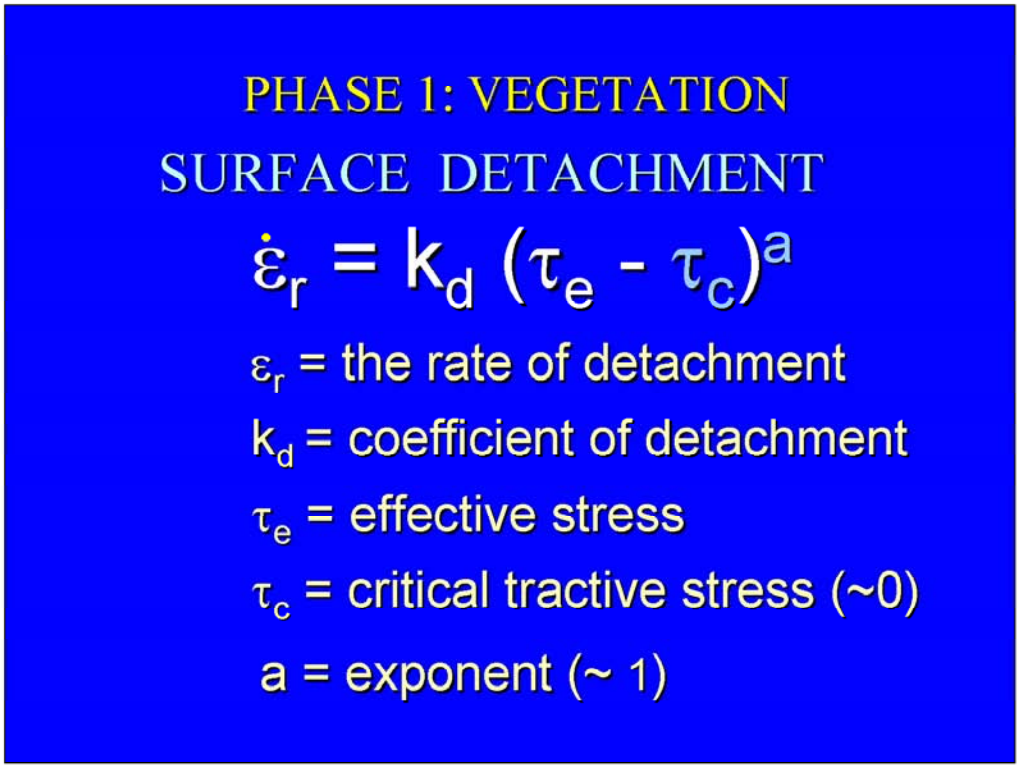
The second phase is a concentrated flow erosion leading to the development of a headcut,

And the third phase is the deepening and upstream advance of that headcut. Each of these phases is described in the model by it's own set of threshold-rate relations.

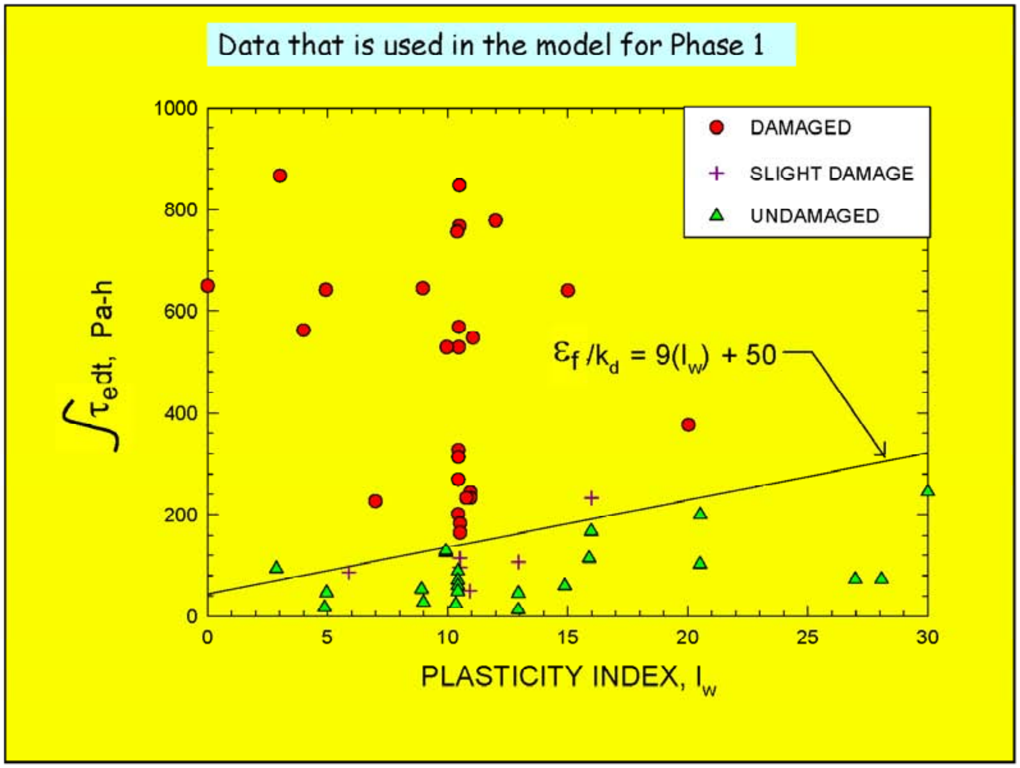
The relations tend to be a somewhat simplified representation of the processes, and I'm going to go through them rather quickly as a lead-in to the weaknesses and research needs.



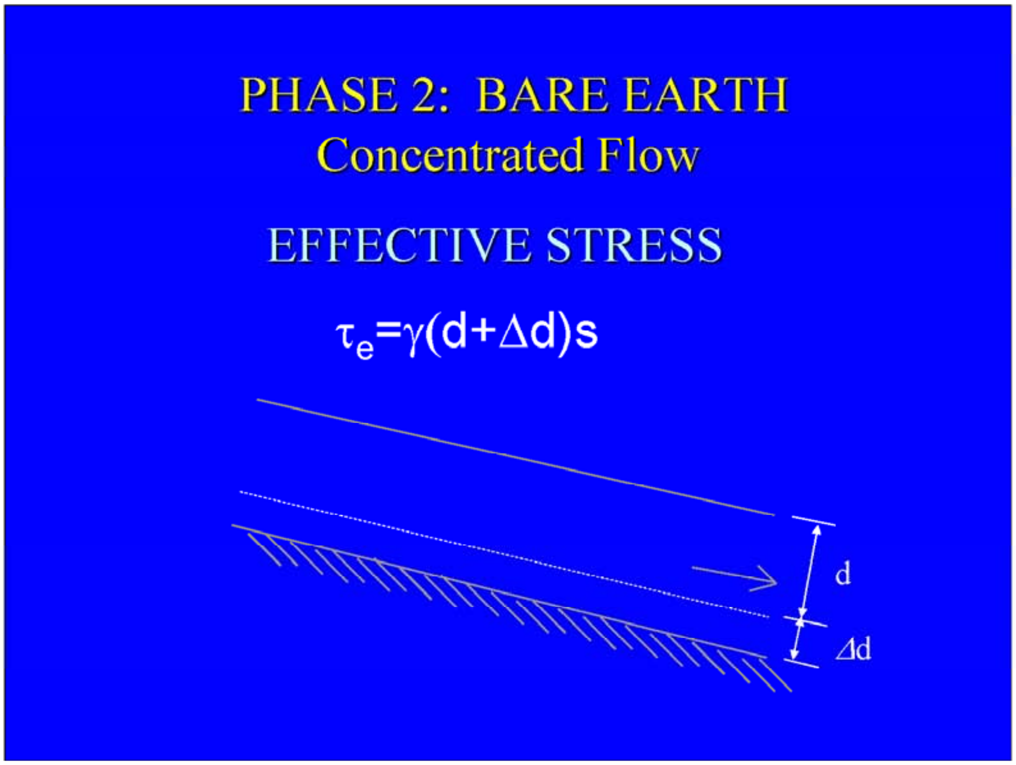
Phase 1 uses an erosionally effective stress approach that computes gross stress from normal depth, gamma d S, and adjusts it for the type of cover 1-Cf, and for the transfer of stress to the boundary by the plant root system ns/n squared.



This is combined with an excess shear detachment rate relation with the critical shear stress assumed to be negligible. The assumptions that the process is detachment limited and the material is fine grained tend to be reasonable because we are applying the relations to spillway flow over vegetation. When the material does not support vegetation, phase 1 tends to be negligible, and we immediately move to phase 2.



The failure point is calibrated to field data, and tends to fit the available data fairly well. Note that the material properties are represented by plasticity index for this phase.



Since phase 2 is also surface detachment, we also use the same stress approach, but now, we assume that all of the stress is effective in detaching material, and account for flow concentration by assuming the water surface elevation in the eroding area is controlled by the surrounding flow.

PHASE 2: BARE EARTH
Concentrated Flow

SURFACE DETACHMENT

$$\dot{\varepsilon}_r = k_d (\tau_e - \tau_c)^a$$

$\dot{\varepsilon}_r$ = the rate of detachment

k_d = coefficient of detachment

τ_e = effective stress

τ_c = critical tractive stress

a = exponent (~ 1)

We also use the same detachment rate relation, but now, the critical stress is a function of particle diameter based on Shields diagram, and Kd is determined explicitly.

PHASE 2: BARE EARTH

Concentrated Flow

DETACHMENT RATE

$$k_d = \frac{5.66\gamma_w}{\gamma_d} \exp\left[-0.121(c\%)^{0.41}\left(\frac{\gamma_d}{\gamma_w}\right)^{3.10}\right]$$

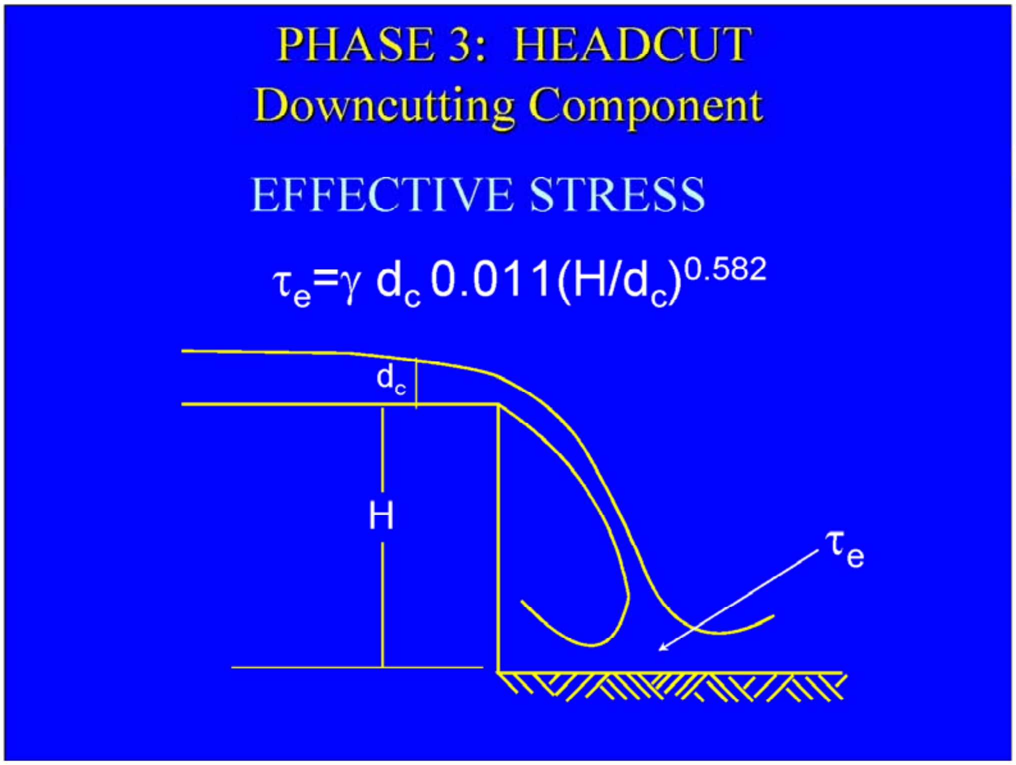
k_d = detachment rate coefficient

c% = percent clay

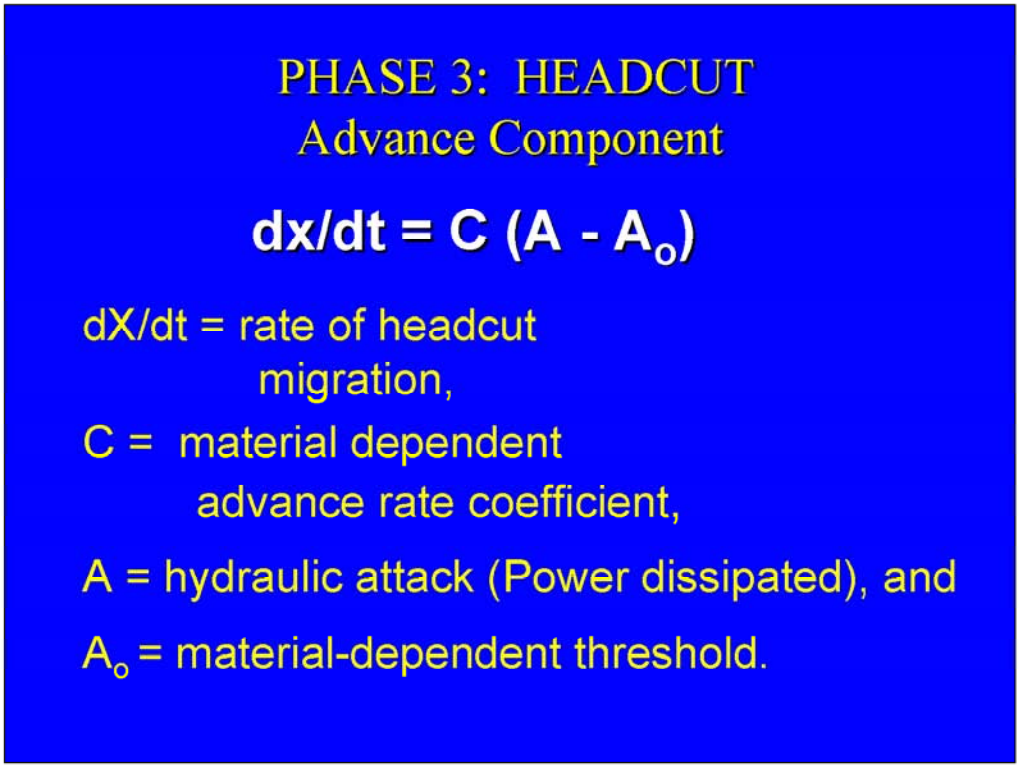
γ_d = dry unit weight

γ_w = unit weight of water

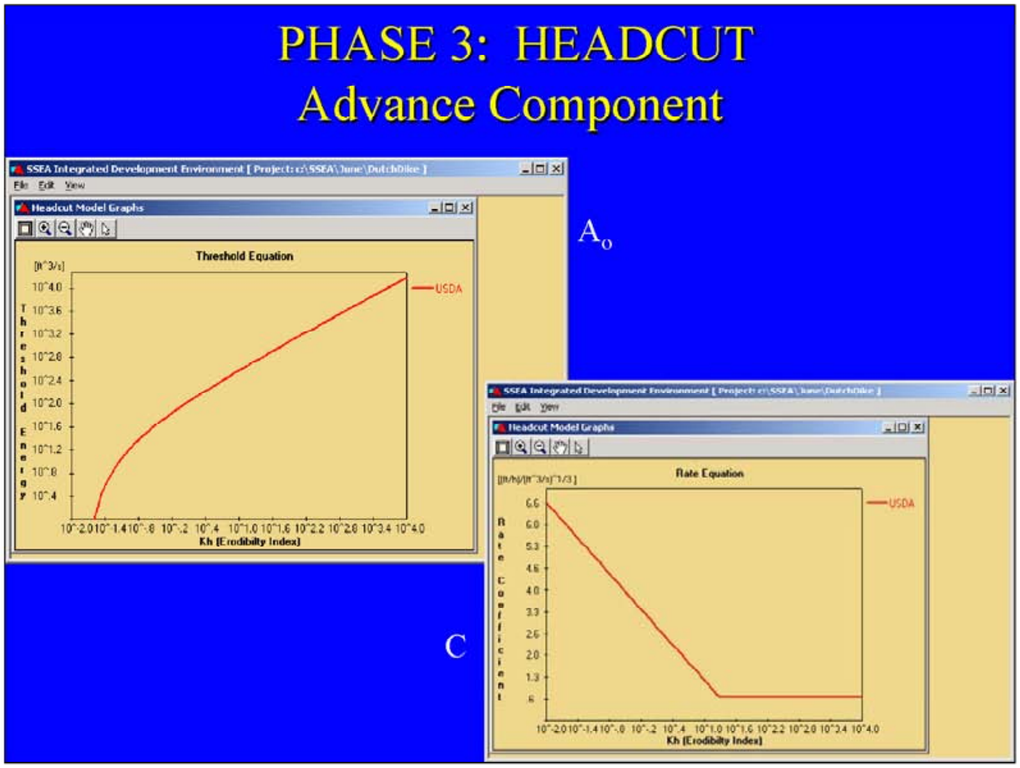
Kd may be measured for soil materials using the jet test for erodibility or estimated from percent clay and density. This means that for soil materials, phase 2 tends to be dominated by the clay and density properties, whereas for rock, particle diameter dominates. We are still assuming detachment limited conditions and concerning ourselves with a point in the spillway.



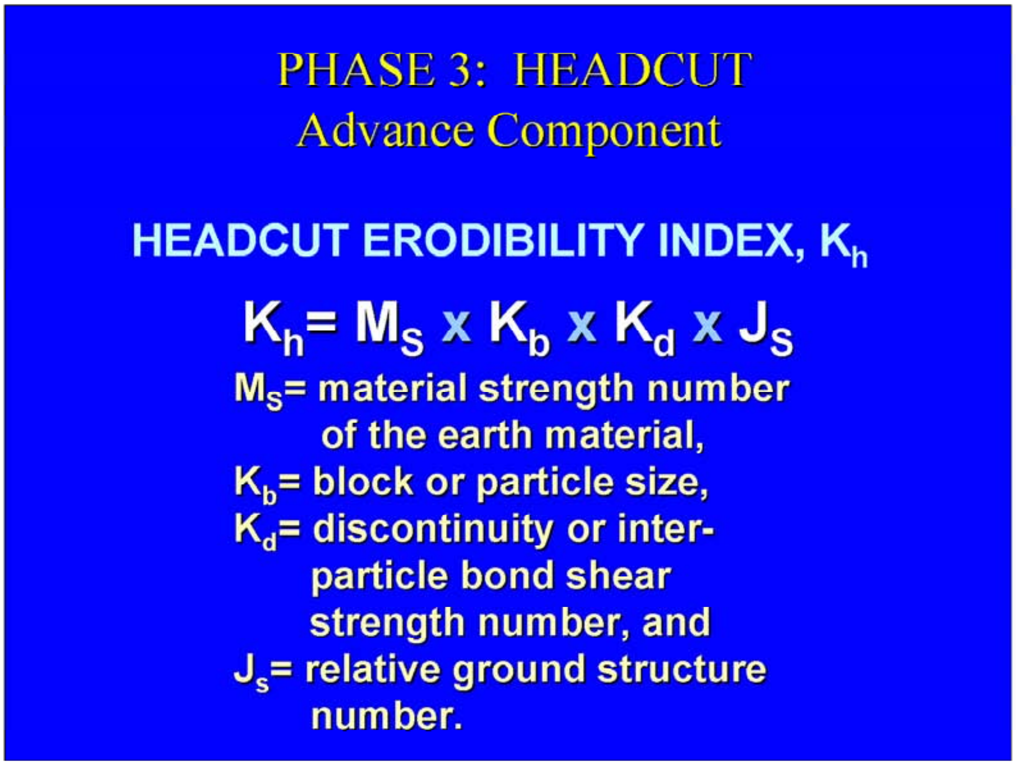
Phase 3 is divided into two parts for computation. The downward movement and the headward movement. For the downward component, surface detachment is taking place, and we continue to use an excess stress approach with the stress computed assuming low tailwater conditions. The detachment rate relation is the same as applied previously.



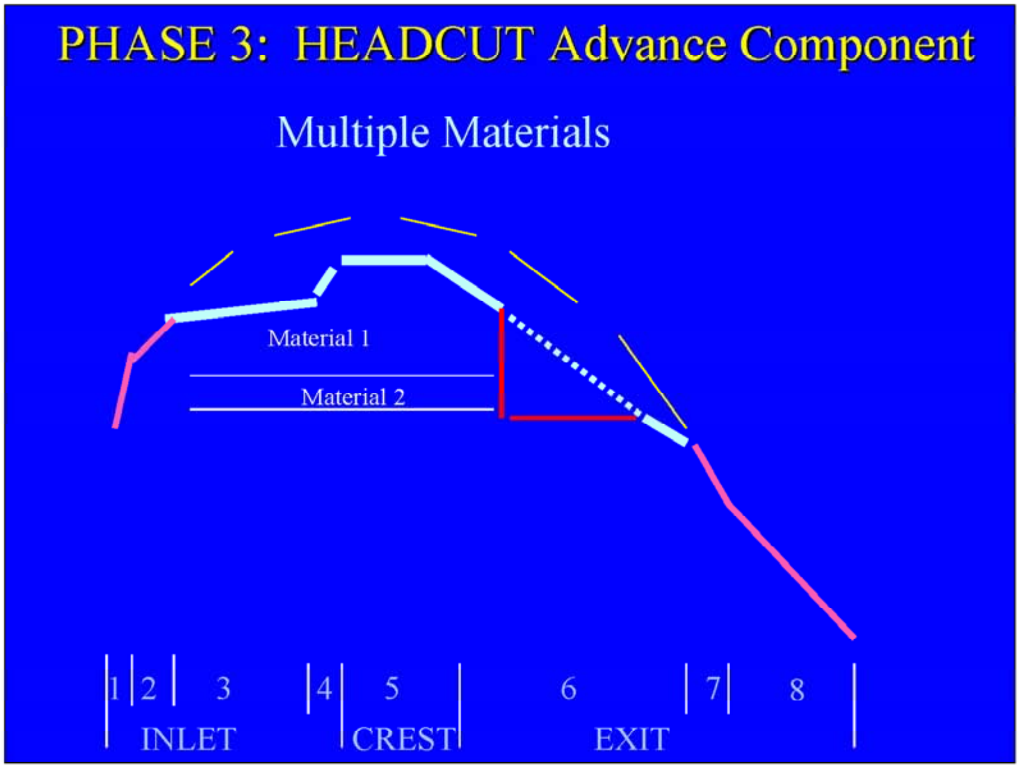
The headcut advance relation is of the same general threshold rate form as the other relations, but is energy rather than stress based. Although several modes of headcut advance have been observed from undercutting to surface detachment on a steep-sloped face, all have in common the focused dissipation of flow energy.



As applied, both the threshold and the rate coefficient are expressed as functions of the headcut erodibility index. This index was adopted from work done in South Africa on material excavability, and that work in turn was built on work in Scandinavia on tunneling. The curves shown here are those developed from data collected over a 10 year period from field spillways on flood control reservoirs. The Corps also used the approach to analyse data from some of their spillways and came up with slightly different curves. We are presently working with Corps researchers in Vicksburg to reanalyse all of our data to see if we can refine these relations.



The index itself is a measure of the overall strength of the material mass. In the interest of time, I'm not going to go over the details, but references are provided in the materials we made available for the workshop.



Of course, spillways never exist in a single material, so use of the relations requires determination of a representative value of headcut erodibility index for multiple materials. Since the index lives in log space, the form of averaging used is

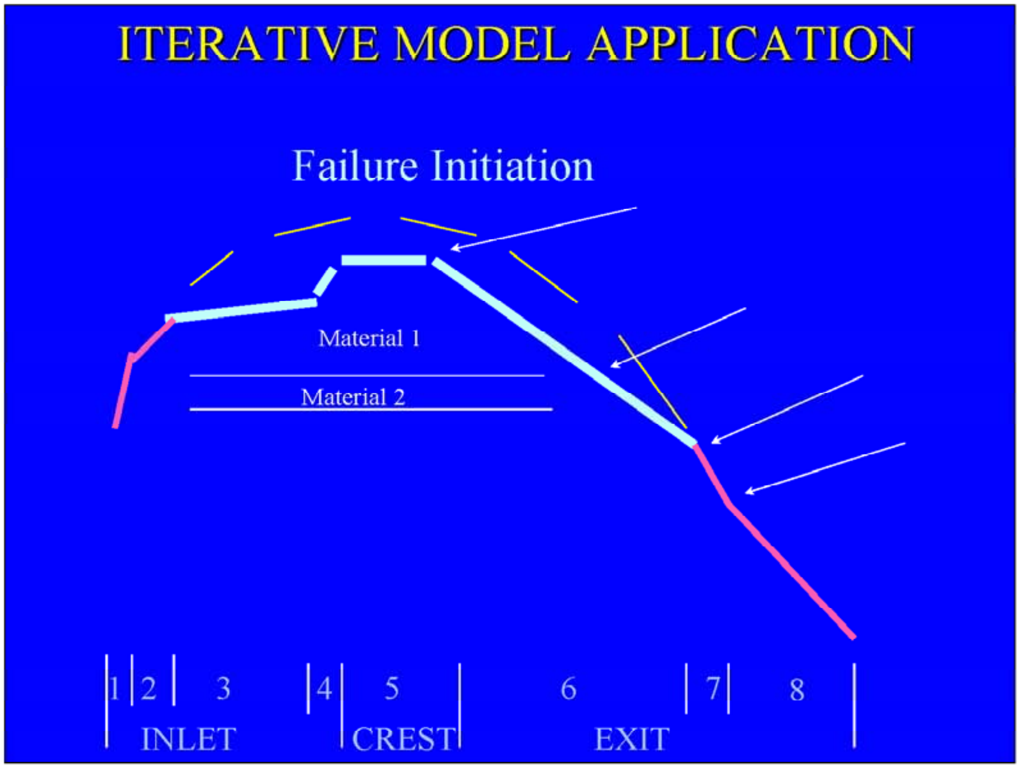
PHASE 3: HEADCUT Advance Component

Multiple Materials

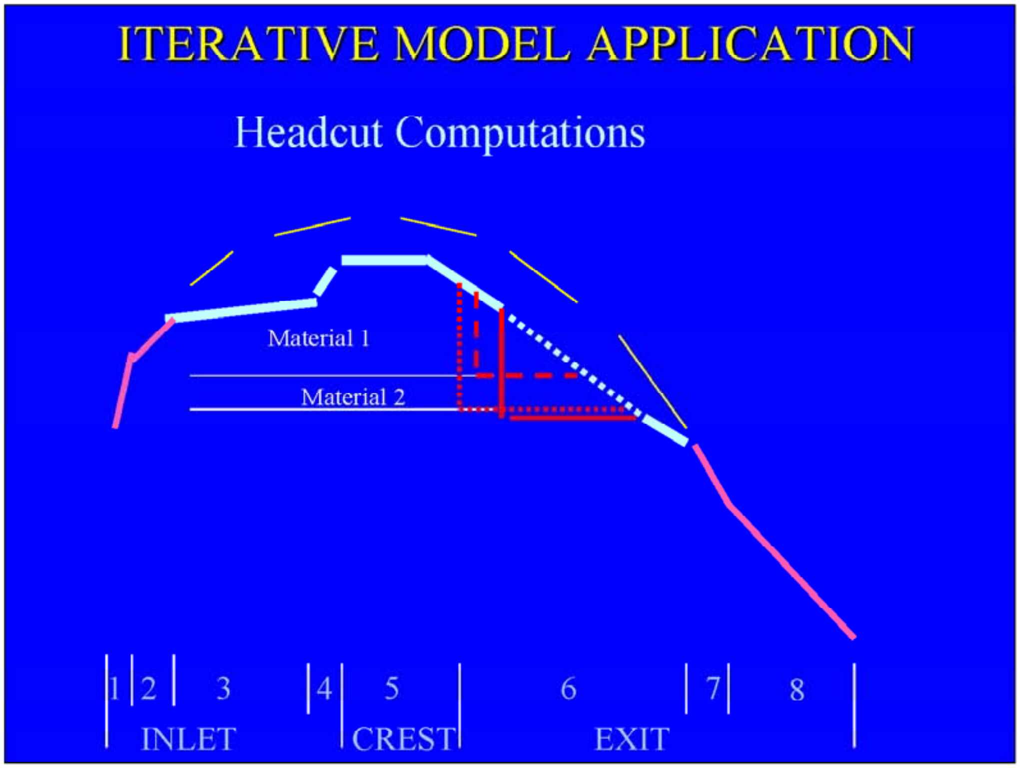
$$K_h = e^{\frac{\sum h_i \ln(K_{h_i})}{\sum h_i}}$$

h_i = the thickness of material i, and
Summation is carried out over all materials exposed on the face

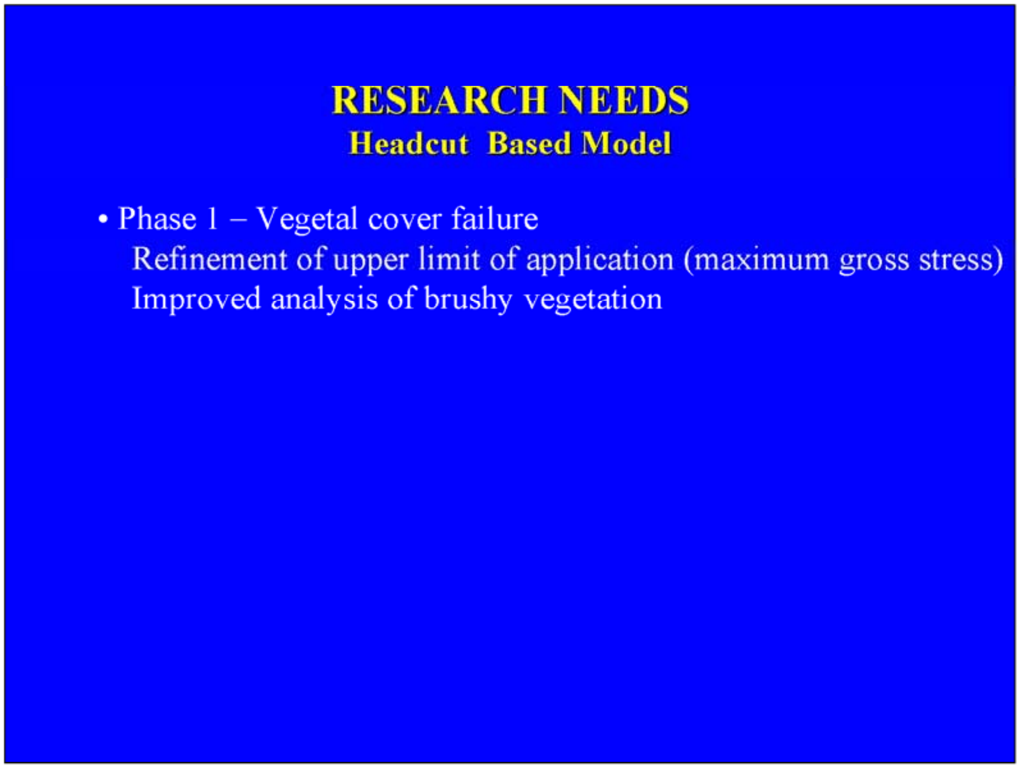
A depth weighted log averaging scheme. This has been found to work surprisingly well.



It is also necessary to apply the method iteratively to determine the worst case condition for location of headcut formation. It is not immediately obvious whether a headcut formed early in the flow at the end of the exit channel will pose a greater or lessor risk of breach than one formed later near the crest. If material 2 happens to be a sand lense, it may also be that the headcut that exposes that material the most rapidly will be the one posing the greatest risk.

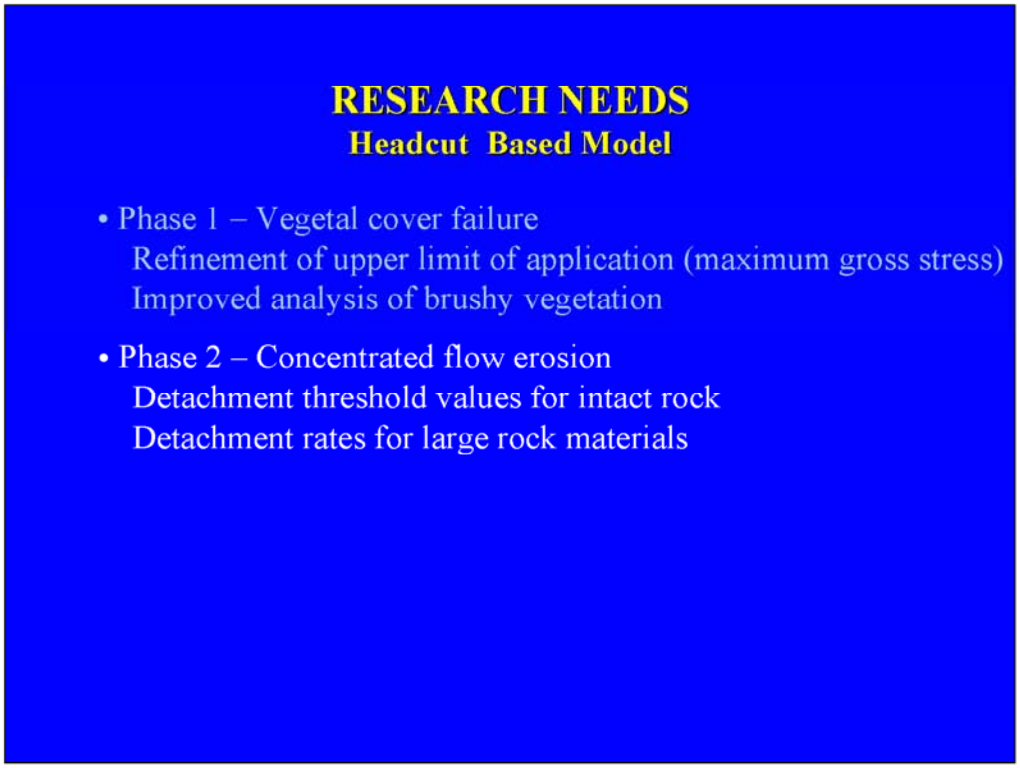


On the other hand, if material 2 is a rock, it may be that a headcut following the upper surface of the material will move more rapidly than one penetrating into or through that material. All of these scenarios must, therefore, be evaluated. In the present model, they are evaluated one at a time as if that headcut were the only one present.

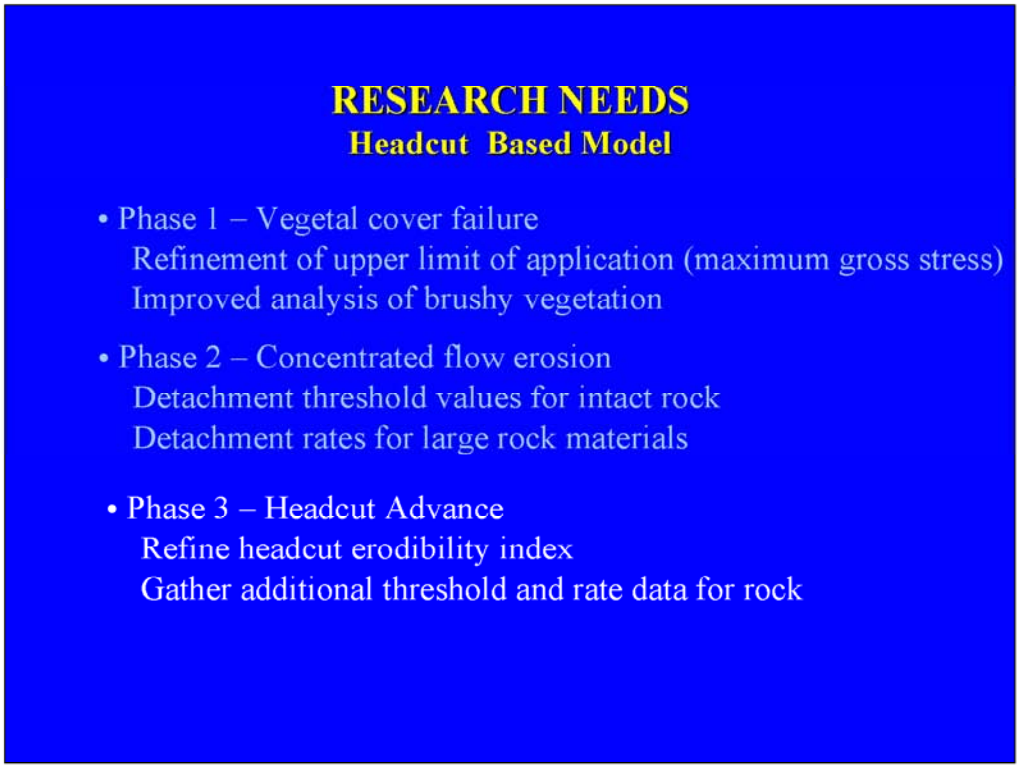


Let me begin the discussion of research needs in the context of the Sites erosion model. And I'll begin by noting that Sites represents a first attempt at quantifying the overall process for field application, and there is no part that couldn't be refined; And we recognize that it does not apply to every spillway problem.

In terms of the phase 1 processes, there are a number of areas that could be improved, but the model is probably consistent with the extent that we normally have information to describe the condition of the surface. Areas where advances could be made include improved determination of the upper limit of applicability of the erosionally effective stress relation; that is At what gross stress does the vegetation begin to experience damage directly?; and improved analysis of the effects of brushy vegetation. The fact is though, that phase 1 plays an important role only for relatively low heads and relatively erodible materials, so the mileage were going to get from refinement here is somewhat limited.

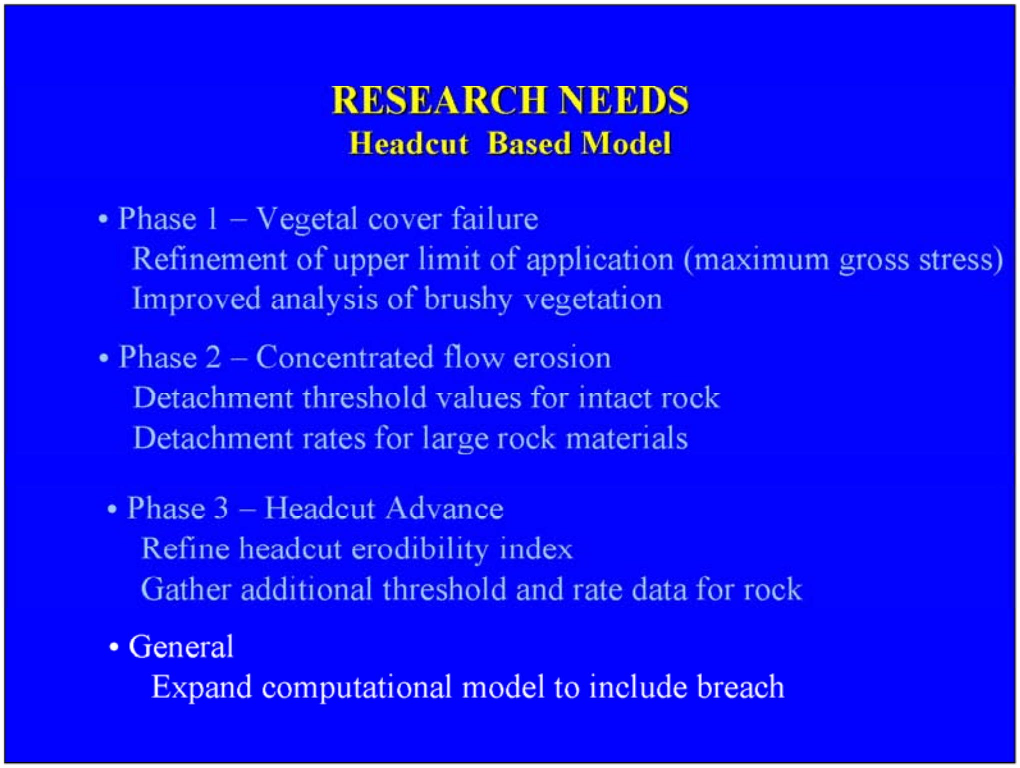


Phase 2 is usually the most important for spillways with rock materials near the surface of the spillway. The present model implicitly assumes loose material (based on diameter only) and will often be over-conservative. The model needs to be refined. This could be done using either stress or energy approaches, but will require data that is rather scarce.



In terms of the downcutting portion of phase three, all of the considerations of phase 2 apply, plus the need to better tie the downcutting and advance parameters together to avoid inconsistent data.

The headcut erodibility index itself needs refinement. USDA is presently working on refining our means of estimating it in the never-never land between soil and rock. However, more fundamental work on the index itself is needed. As it presently exists, it was simply adopted from excavability applications. The processes are similar, but not identical. The index was named as it is so that future modification would be possible without confusion with other application related indices.



A more general need that has been identified is to expand the model to include breach computations in such a way that we could account for the ability of changing geologic materials to stop complete breach. If you think about what is involved, that is no small task. We could also expand to talk about three dimensional geology, tailwater effects, air entrainment effects, etc., but those would require substantial advances in material mapping and description before inclusion in a general application model could be justified. Some of these issues are addressed in the publications included in the list provided to the workshop.

The three phase model with with headcut advance to breach represents a major portion of the earth spillways observed to have experienced damage. However, it does not represent all conditions. For example, this spillway in volcanic rock eroded due to abrasion in areas of reverse flows where potholes were developed. This type of erosion is not addressed at all in the Sites Model. Likewise, long flat sloped spillways in material where sediment transport is an issue are not properly analysed by the Sites model, because Sites assumes detachment limited conditions and movement of the detached material out of the immediate area.

We could go on much longer with this, but I'll stop with this one last comment. All of the available models are simplified and we seldom know exactly what materials will be exposed during the erosion process. This uncertainty needs to be evaluated along with the uncertainty related to the flow conditions. Some work is going on now at Vicksburg in this area, but spillway erosion analysis is still in its infancy. We still have much to learn.