The effect of material zones and layers on breach growth and prediction

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Abstract

Breach prediction models have typically focused on the prediction of processes through homogeneous structures (levees and dams), with some allowing for the effects of surface protection layers (such as grass or rock) and in some cases, the effects of simple core structures. Even with these simple models, it can be seen that the effect of surface layers or cores can be significant. The impact of changes in the rate of breach erosion are often magnified by the way in which these changes affect the breach growth timing in relation to the hydraulic load; for example, whether the main breach formation phase occurs as flood levels rise, peak or pass and drop.

The EMBREA model was developed to allow breach prediction through levees and dams constructed from zones of material. The model evolved from the earlier HR BREACH model and combines flow, soil erosion and slope stability calculations. Whilst the model can predict both headcut and surface erosion processes, the zoned behaviour is currently limited to the surface erosion simulation process. Simulations using different zoned geometries shows behaviour that is consistent with aspects of different homogenous breach processes, however, as the different zones erode, the characteristics also change. The effect of integrating erosion and breach growth processes through different zones of material gives results which can differ significantly from breach prediction through simple homogenous structures. This emphasises the importance of modelling real, zoned rather than simplified structures.

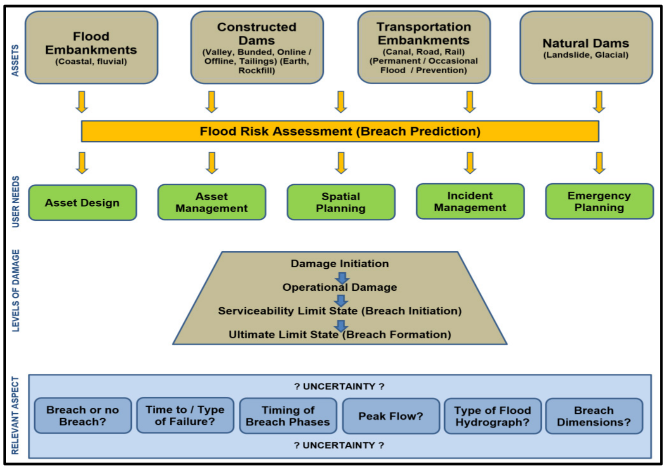
Whilst the significance of zoned breach prediction can be seen, the need to understand, refine and validate the way in which we model these processes remains a top priority. As with earlier models, the rate of erosion depends upon the soil erodibility (K_d) for which we need to confirm the most appropriate erosion relationship(s). With zoned structures, the nature of the soil zones can vary from erosion resistant clay cores to highly porous rockfill material. With macro erosion processes changing from headcut to surface erosion to rockfill slumping, the need to understand why and when the erosion process changes in relation to soil type and grading remains very important. To confirm and validate these processes, large scale laboratory and / or field testing of both homogeneous and zoned structures is required.

1 Introduction

Breach prediction models have typically focused on the prediction of processes through homogeneous structures (levees and dams), with some allowing for the effects of surface protection layers (such as grass or rock) and in some cases, the effects of simple core structures. Even with these simpler models, it can be seen that the effect of surface layers or cores can be significant. The impact of changes in the rate of breach erosion are often magnified by the way in which these changes affect the breach growth timing in relation to the hydraulic load; for example, whether the main breach formation phase occurs as flood levels rise, peak or pass and drop.

The effect that zones of different material, or similar materials but in different states of compaction, has on breaching processes can also be shown to be very significant. With a wide range of different users and end applications of breach prediction models (Figure 1), it is important to recognise these effects and take them into consideration when predicting breach.

Figure 1. Different end users and applications for breach models



This paper provides a quick reminder regarding key breach formation processes and then goes on to show prediction of breach through zoned structures using the EMBREA breach model. These results highlight the significant effects that zoning can have on breach formation processes. With these observations, recommendations as to the next steps for developing and validating breach models for zoned structures are presented.

2 Key factors affecting breach formation

Four aspects affecting the overall breach formation process are highlighted in this section. These are emphasised because of how they are influenced by, or will influence, the way in which breach models may predict breach through zoned structures. These factors comprise:

a) Macro erosion processes
b) Effect of surface layer protection
c) Soil erodibility in relation to draw-down rate
d) Effect of thin cores

2.1 Macro erosion processes

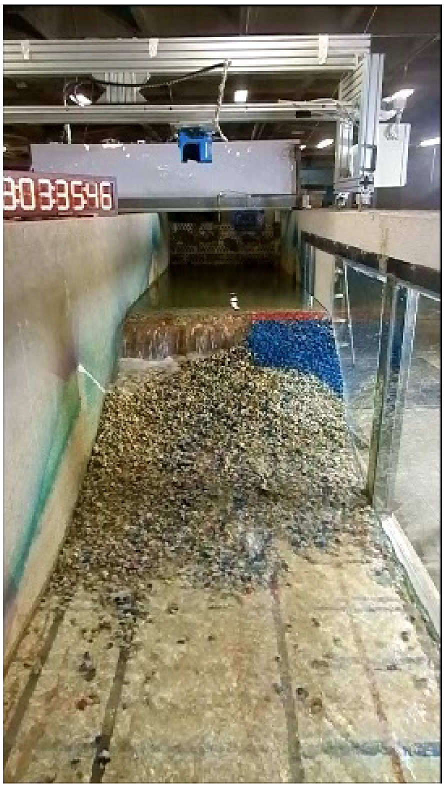
Macro erosion processes are the large scale (visible) processes that occur during the overall breach formation process. These comprise (i) headcut; (ii) surface erosion; and (iii) rockfill slumping (Figures 2-4).

Figure 2. Headcut erosion (Photo: USDA, Greg Hanson)

Figure 3. Surface erosion (Photo: IMPACT Project)

The significance of these different processes is the point at which erosion affects the rate of overflow – i.e. the point when the crest level controlling the overflow discharge is affected. Within a zoned structure, two or even three different macro processes may occur during the overall breach formation process.

Figure 4. Rockfill slumping (Photo: MA Toledo)



2.2 Effect of surface layer protection

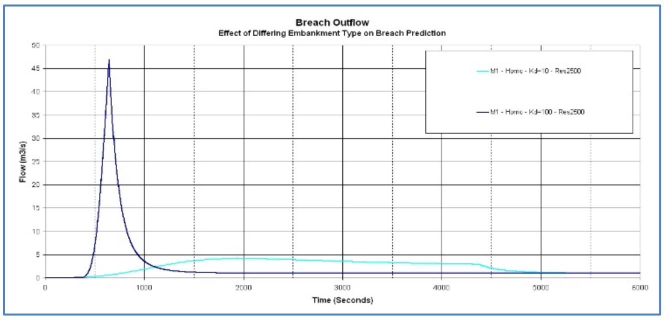
The immediate effect of surface layer protection will be to delay the onset of erosion – for example, grass cover delaying the initiation of soil erosion beneath. However, some forms of cover may also induce different rates and location of erosion by delaying and / or focussing erosion in specific ways (Figure 5).

Figure 5. Erosion behaviour at a small dam affected by soil type and road cover (appears dominant) and transitions between soil and various structures (Photo: Alan Brown)

2.3 Soil erodibility in relation to draw-down rate

The combination of soil erodibility and potential draw-down rate is what determines the characteristics of a breach flood hydrograph. Figure 6 shows two plots of breach outflow for the same reservoir and dam geometry, but with different soil erodibility. For the 'peaky' flood hydrograph, the breach invert erodes down faster than the reservoir water level can draw-down. For the long, low flow hydrograph, the breach invert erodes at a rate similar to or slower than the potential draw-down rate. The product of K_d and A_{res} (soil erodibility and reservoir surface area) is a key parameter reflecting the breach hydrograph characteristics.

Figure 6. Example of two breach flood hydrographs – same reservoir and dam geometry; different soil erodibility



2.4 Effect of thin cores

The effect of thin cores within levees and dams (Figure 4) is to delay the progression of erosion (as with surface protection layers). However, eventual failure of the core can then result in a sudden, step increase in discharge as the crest flow control fails in a catastrophic manner.

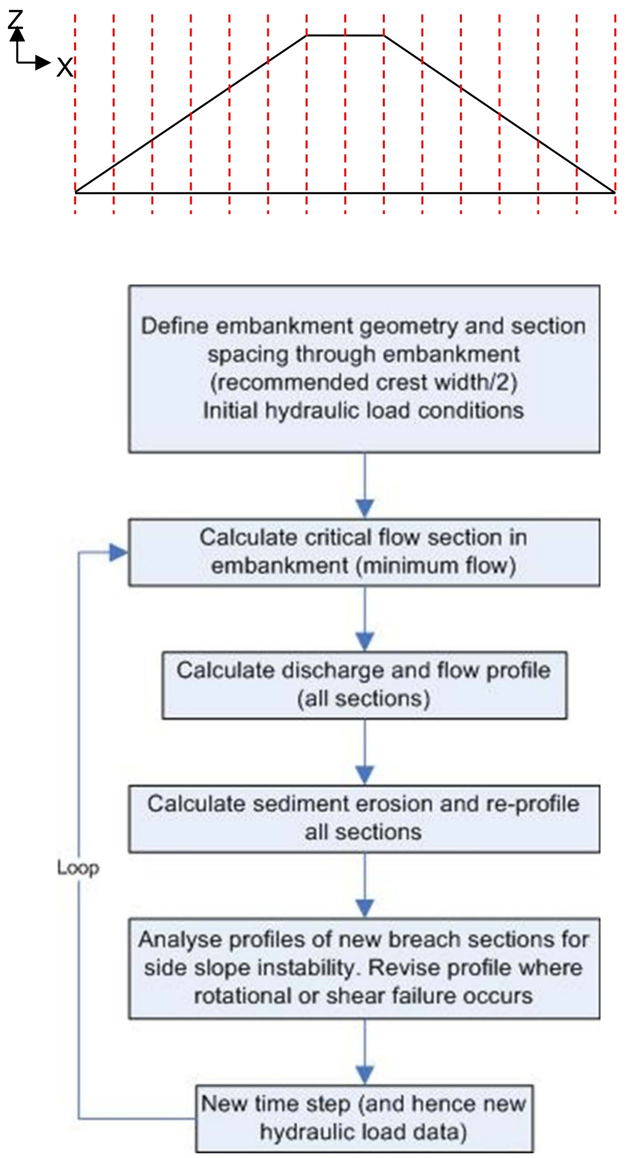
In the following sections the EMBREA zoned breach model is introduced and the results from zoned simulations presented. The characteristics of breach arising from the zoned simulations should then be considered in relation to the characteristics presented in Sections 2.1-2.4 above in order to recognise how the zoning of materials affects the breach formation process.

3 The EMBREA breach model

The EMBREA breach model was developed to allow breach prediction through levees and dams constructed from zones of material. The model evolved from the earlier HR BREACH model and combines flow, soil erosion and slope stability calculations. Whilst the model can predict both headcut and surface erosion processes, the zoned behaviour is currently limited to the surface erosion simulation process.

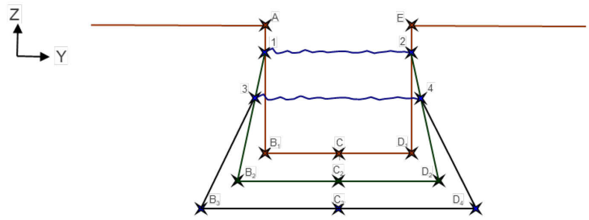
The model defines sections through the dam or levee and then follows a process of flow, erosion and section profile calculations as shown in Figure 7 below.

Figure 7. Overview of HR BREACH and EMBREA model calculation process



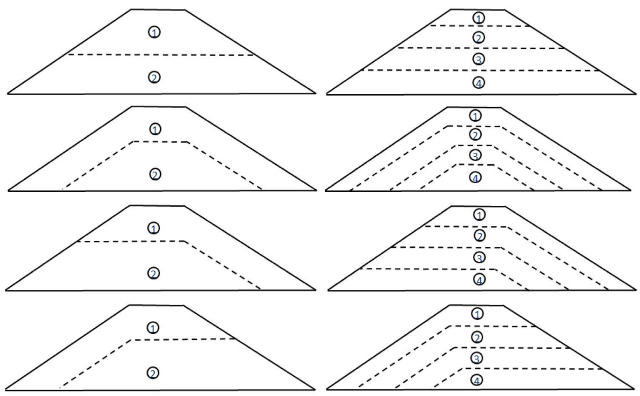
At each section the model calculates the bed shear stress from previously calculated flow conditions, subsequent erosion (using the chosen erosion relationship) and then the new section profile (Figure 8). The section profile leads to lowering of the bed and undercutting of the sides. Side block failure is then accounted for through analysis of the conditions for shear or rotational slip failure. Each section is free to evolve according to the flow and erosion conditions occurring at each time step.

Figure 8. Breach section evolution



Whereas the HR BREACH model simulated overflow (or internal erosion) through a homogeneous or thin cored levee or dam, EMBREA was developed to simulate overflow and internal erosion through different zoned geometries (Figure 9).

Figure 9. Example of levee and dam zone geometry options within EMBREA

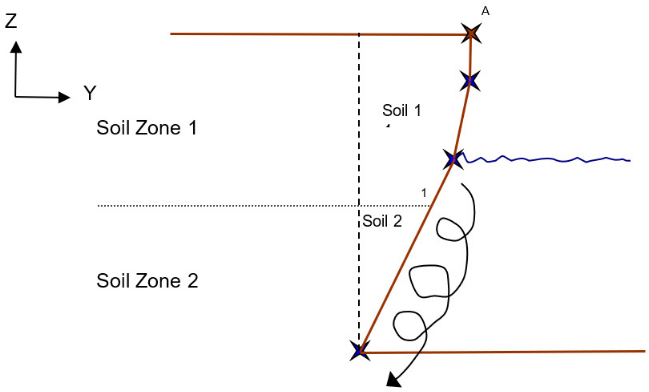


When developing the model procedures for predicting how erosion might develop through different combinations of soil erodibility and geometry, a key assumption was to calculate erosion within the breach opening upon using the erodibility of the exposed soil at the base of the breach, and not of other zones or layers exposed higher up within the breach. This assumption was based upon observations of how breach erosion typically occurs through very turbulent vortex action around the base of the breach sides (Figure 10).

Figure 10. Breach erosion by vortex action undermining breach sides (Photo: IMPACT Project)

Whilst the base soil erodibility was used to establish rates of section erosion, any combination of soil zone properties was used to assess side slope stability and block failure (Figure 11). When block failure occurs, all material is (typically) assumed to be removed instantaneously.

Figure 11. Breach side slope erosion and stability calculation using multiple zone soil properties

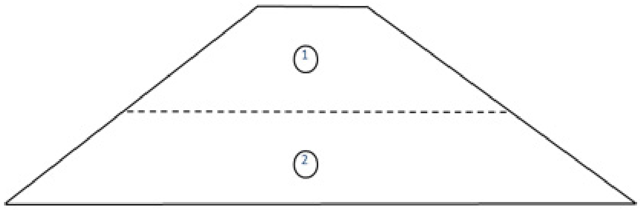


4 Zoned simulations

A number of different zone geometry simulations were undertaken using the EMBREA model and compared with results obtained using an identical geometry and hydraulic load conditions. The results show how breach predictions are significantly affected by the consideration of different zones.

The example scenario used to generate the results for a homogeneous structure, shown in Figure 6, was also used to simulate the results for a zoned structure, where two layers of different erodibility material were considered (Figure 12).

Figure 12. Simple 2-zoned structure



The original dam was defined as 4m high; the new zoned scenarios considered 2 layers (a) each 2m thick and (b) 1m plus 3m thick. The erodibility of each layer was assumed to be either a K_d of 10 or 100 (i.e. 10 times more erodible). The simulation results showed erosion processes consistent with what might be expected to occur (Figure 13). The top three images show erosion progressing where the upper layer is more erodible than the lower; the lower three images show the reverse case.

Figure 13. Model predicted erosion process

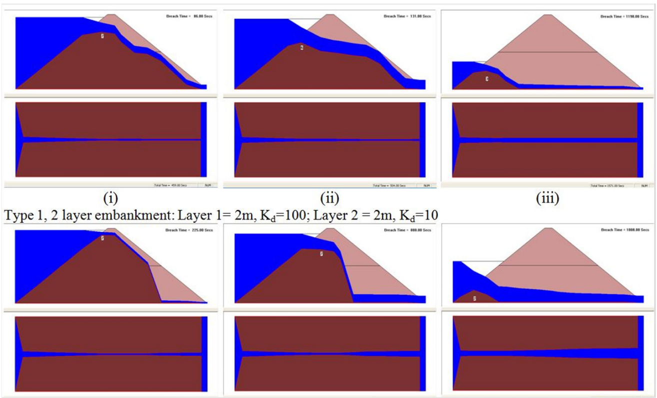
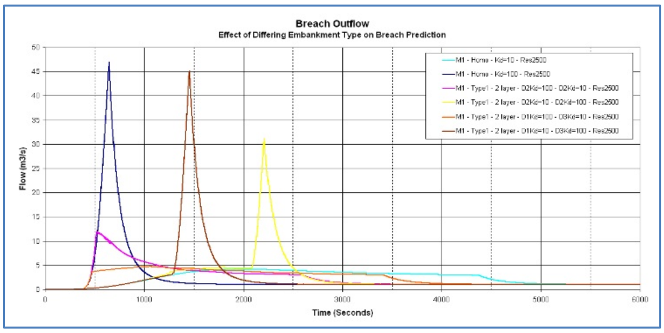
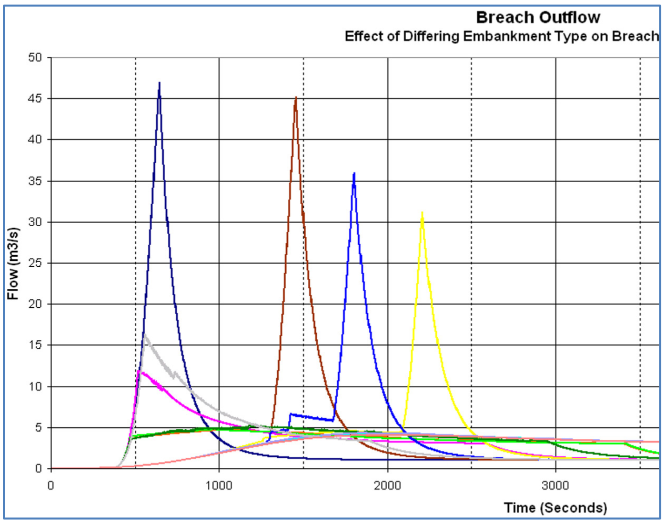


Figure 14. Predicted breach outflow hydrographs

(a) Full plot; (b) Expanded view of detail





The predicted breach flood hydrographs show a range of behaviour that fits within the ranges predicted for the original homogeneous structure (Figure 14). It can be seen that, for example, with an erodible top layer, the hydrograph characteristics initially follow those of the erodible homogeneous structure, but after a period of time tend back towards the less erodible homogeneous structure hydrograph. Similar behaviour can be seen with the other zoned combinations, resulting in a set of hydrographs which vary significantly, but which fit between the original extremes shown in Figure 6. Further simulations undertaken with different zoned combinations gave differing flood hydrographs, but all remained between the two extremes in Figure 6.

5 Conclusions

The EMBREA breach model has been developed to simulate breach formation through zoned structures. Initial results are consistent with what might be observed in the field. This initial approach to modelling breach through zoned structures has highlighted a number of points including:

i. The breach flood hydrograph characteristics depend upon a combination of soil erodibility and potential draw-down rate of the upstream area. Varying these factors shows that the breach flood hydrograph can vary from a rapid, high peaked surge to a much slower release of water, for the same dam or levee structure and upstream load conditions.
ii. Introducing zones of different material erodibility into a structure can have a significant impact on the timing and shape of the breach hydrograph.
iii. It appears that variations in zoned breach behaviour ‘sit between’ the two extremes of hydrograph that may be predicted for the identical homogeneous structure, with different soil erodibilities.

These findings suggest that zoned structures have a significant impact on the way in which breach formation occurs. Simpler methods of breach prediction will not highlight these differences. Indeed, the actual processes might vary even more significantly when macro erosion processes change within the breaching process for a single structure. However, current modelling ability does not yet permit us to predict these process changes.

In order to validate these findings and to further improve the accuracy of breach process prediction, the following research actions are recommended:

i. Medium to large scale tests to determine the factors affecting macro erosion process changes (in relation to soil grading, soil erodibility etc).
ii. Large scale test data showing zoned structure erosion processes, allowing the erosion process between different geometries and soil erodibilities to be better understood,

References

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