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PRACTICAL PROBLEMS IN THE ASSESSMENT OF GENERAL SCOUR IN RIVERS: A PRACTIONER'S PLEA FOR MORE RESEARCH

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When river crossings are being designed reliable predictions are required of the likely general scour and bend scour depths for different flow conditions. At present there are a variety of methods available for predicting general scour and bend scour however they all make a number of fundamental assumptions that greatly affect their outcomes. When predicting general scour it is assumed that: the flood level is maintained, channel shape remains the same, the effect of contraction or longitudinal variation is ignored, and that there is no effect due to armoring of the sediment bed. When predicting bend scour it is necessary to understand the scour process and identify for which flows scouring is likely to occur. It is currently assumed that the bankfull flow condition is critical for estimating maximum bend scour depths. To estimate the appropriate depth a pipeline must be buried beneath a river it is then necessary to combine the results of the general scour and bend scour analyses. However, there is currently little information to justify many of these assumptions. Thus when the maximum total scour depth must be predicted there is uncertainty in both the methodology for prediction and also in how and when to combine the predicted scour depths. This paper will discuss each of the assumptions made in the general scour and bend scour prediction methods and, where possible, propose procedures for reducing the uncertainty surrounding the scour depth assessment. Recommendations are also made for future research to improve both the prediction methods and their application, in predicting general scour at river crossings.

1 Introduction

The design of river crossings requires the prediction of likely scour conditions that may be experienced over the design lifetime of the structure. This requires the choice, application and interpretation of the appropriate scour prediction methods for the river channel. Of particular interest are prediction methods for estimation of general scour and bend scour.

At present there are a number of different methods available for the estimation of general scour and bend scour in river channels, although each method makes a number of fundamental assumptions that can affect their outcomes. The purpose of this paper is to identify issues related to the application and interpretation of these scour methods and it is hoped this will act as a stimulus to researchers in this area.

For the purposes of this discussion, general scour is defined as the general lowering of the sediment bed that can occur during the passage of a flood wave. Long-term general degradation of the river channel is beyond the scope of this work. Bend scour is defined as the scour process associated with the flow of water around a bend in the river. It can cause the bend to migrate downstream and also possibly laterally.

Both types of scour process, their prediction methods and issues related to the various prediction methods are discussed separately and also comments are presented as to how they may be combined to give an overall assessment of scour depths for the design of a river crossing.

2 Prediction of general scour

General degradation of the riverbed can occur during flood events, where the flow rate is increased and the sediment transport capacity of the flow exceeds the supply. In order to predict the magnitude of the likely change in sediment bed level a number of assumptions are made, including:

- The flood level is maintained after scouring has occurred.
- Channel shape remains the same.
- Representation of contraction/longitudinal variation.
- There is no effect due to armoring of the sediment bed.
- The methods used are applicable for extreme flood conditions.

In this section, each of these assumptions will be discussed and their impact on the overall uncertainty in the estimation of general scour depths will be described.

2.1 Flood level changes

Most methods for predicting general scour contain the assumption that the flood level with scour is the same as the flood level without scour. This is unlikely to be true. As the channel bed level changes then there may be a corresponding change in the flood level.

In order to assess the implications of scour depth on flood level, a number of tests were performed using a one-dimensional model of a river where previous estimates of general scour depths had been made.

The original general scour assessment was done using the procedure outlined in May, Ackers and Kirby (2002). Flow depths and velocities for each cross-section were obtained from the one-dimensional model results. Using this information (termed 'original'), the following procedure was then used to assess the effect of changes to the bed level on flood levels:

- Assess the scoured depth for each flow zone in the channel cross section.
- Redistribute the scoured area and redraw the channel cross section.
- Rerun the model and assess the flow depths and velocities
- Compare to the original flood levels and flow velocities
- Check scour depths and repeat process if necessary

Table 1 outlines the results of this assessment of scour depth on flood level (for a 200-year return period flow) for three different test cases as well as the original model, where no bed level change was modeled. The difference between each of the three cases tested is in the redistribution of channel shape, as shown in Figure 1. The flood level and depth-averaged flow velocity are compared to the original situation (where no bed level change has been applied to the model). The flow area of each of the models is compared to the original scoured channel area predicted using May, Ackers and Kirby (2002).

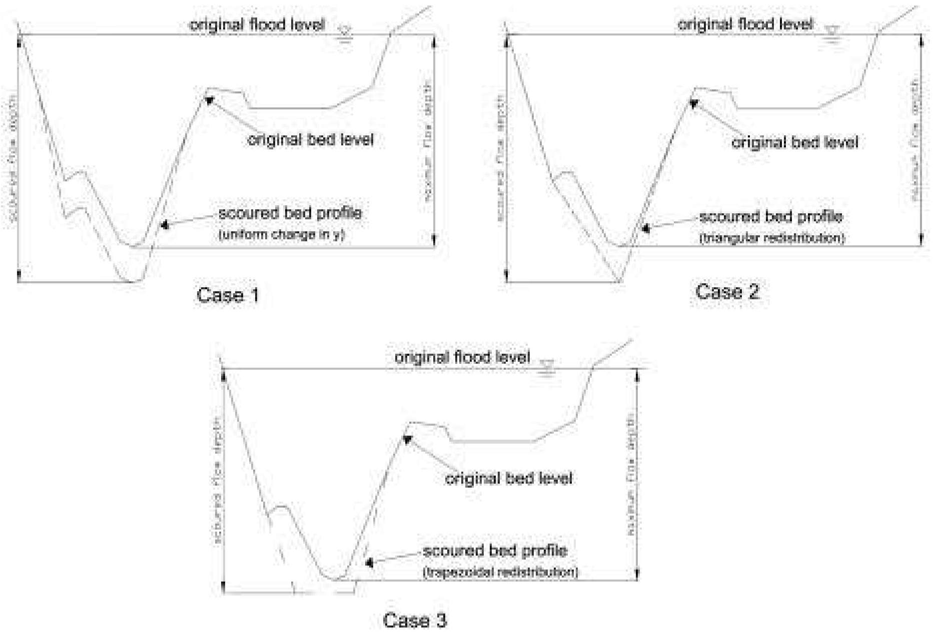

Figure 1. Scoured channel profiles used in Test cases 1, 2 and 3.

The results show that for all cases tested (the 3 different choices of redistributed channel area) a change in flow depth and, therefore, change in flow velocity did occur when the shape of the channel was adjusted to take scouring into account. The flow depth for case 1 has reduced by 1.18m, compared to an original predicted scour depth of 1.15m, which therefore indicates an underestimation of the general scour depth of around 100%.

Table 1. Results of initial tests of the effect of scoured channel changes on flood levels.

Case	Flow depth (m)	Difference in flow depth compared to original (%)	Depth averaged flow velocity (m/s)	Difference in velocity compared to original (%)	Main channel flow area (m^2)	Difference in main flow channel area compared to original (%)
original	3.38	-	2.23	-	103.71*	-
1	2.20	-35	2.96	+33	50.05	54
2	4.41	+30	2.04	-9	96.5	7
3	4.30	+27	2.31	-4	96.7	7

*this value is the required flow area as predicted using the method of May, Ackers and Kirby (2002).

Cases 2 and 3 are very similar, both showing an increase in the flow depth of the order of 0.73m to 0.92m, which is approximately 30% greater than the original model. This can be compared to the predicted scour depth of 1.15m and shows that the original model overestimates the likely scour depth by around 20% to 28%.

These results show that the change in level associated with the scouring of the sediment bed does change the flood level and this has implications for the prediction of the likely general scour depth. It is also clear that the choice of scoured channel shape/area has a significant effect on the results.

When applying this methodology to the scour assessment a number of issues were identified and are discussed below.

- Multi-channel systems - For most general scour calculations the scour depth is calculated for the main flow channels in the cross section. Often a shape factor is applied and this is also generally based on the main flow channel(s). Where the cross section consists of multiple channels the scour depth must be calculated for each channel, which is time consuming but not a problem in itself. The main difficulty in a multi-channel system is the choice of scour depth prediction method, as none of the methods currently available were developed for these systems. For instance, applying the regime type method of White et al (1981) is suitable for the main flow channel(s) but once the flow moves out of bank into the flood plain the applicability of the method has not been tested.
- Scoured channel shape - For general scour methods that are based on the assumption that scour takes place until some area, flow velocity relationship is achieved then some assumption has to be made about the shape of the channel. Melville and Coleman (2000) summarise possible channel redistribution methods. Most methods suggest a simplistic manual redistribution of channel area but there is no rational approach as to how this redistribution should be made. E.g. Harris (1988) states that the scoured cross section is likely to be rectangular or trapezoidal for straight reaches while Neill (1973) indicates that on straight reaches the cross-sectional shape will be parabolic, and that gravel rivers tend to be more triangular in shape. There is also nothing to indicate the time scale of these changes and whether all the changes would occur during a single flood event. In addition, none of the suggested scoured channel shapes specifically mention lateral changes. Armoring and overbank flow will also alter how the channel adjusts to high flow conditions.
- Single cross-section application - Because changes in one section of a river will potentially cause changes in other channel sections both upstream and downstream as well as changes to the flow and energy slopes, the procedure should, perhaps, be applied to all channel cross-sections modeled. This would require each cross-section to be assessed for general scour and then scoured channel shapes to be applied. As with the multiple channel systems, this in itself is not a problem but is time consuming to apply. Also, each channel's redistributed shape must be chosen and this increases the uncertainty in the results. For the tests undertaken only the cross-section under assessment was altered. The effect of not applying the process to all the river cross-sections modeled was seen in the testing. There was a significant difference in the shape of the sections upstream and downstream of the assessed section and a high number of interpolated sections were required. Also, the change in channel slope caused the flow to become supercritical in areas where possibly this may not have occurred if all the sections had been altered.

  There are also arguments for not applying the method to all the channel cross-sections, as a potential feedback system may operate, whereby eroding sections of channel provide a sediment supply for downstream reaches. Doyle and Harbor (2003) review previous studies and conclude that in reality it is likely that upstream degradation and downstream aggradation occur together and the relative magnitude of the upstream and downstream channel adjustments is a function of the channel properties.

2.2 Representation of contraction/longitudinal variation

General scour is that scour that takes place during a flood due to the shape of the channel. A component of this is scour due to a contraction or longitudinal variation in the channel properties. At present most methods of estimating general scour are based on a single cross-section. The information contained within a single cross-section cannot provide any information about the longitudinal variation in the channel properties and so cannot provide the basis for estimating the scour that takes place due to longitudinal variations in channel properties.

It appears that any such prediction method needs to have as data information from a number of points along the length of the river channel. If the data were in the form of cross-sections then this would imply that at least two cross-sections would be required.

In analyses of scour at contractions a distinction is often made between scour at short and long contractions. If this can be extended to natural river channels then this would imply that at least three and possibly more cross-sections would be required to describe the nature of the river channel. The implication is that any method of estimating general scour based on a single cross-section must be inadequate. The conclusion must be that there is a need to improve the representation of scour due to longitudinal variations in channel properties and, in particular, at contractions.

2.3 Armoring

Particularly in gravel bed rivers, armoring of the sediment bed may influence the likely general scour depths. The coarser stones of the armor layer protected the finer sediment from being carried away by the flow.

There are a couple of methods available to estimate armored scour depths, such as those of Pemberton and Lara (1984) or Borah (1989). These methods are based on estimating the threshold sediment size whereby armoring will occur. They require detailed information on the sediment size distribution.

These methods can be used to estimate the effect of armoring on general scour depths; however, there are a number of questions that about the formation of an armor layer.

- If the bed is armored before the flood flow occurs will this remain stable during flood flow conditions?
- Can a stable armor layer form for changing flow conditions, such as a flood wave?
- Work by Ettema (1980) on local scour in layer sediments found that where the scour breaks through the armor layer the resulting scour depth in the finer sediment is greater than it would be for the fine sediment alone. Is this because of sediment deprivation caused by the surrounding bed being armored? Is it a time dependent function? Does this apply to general scour situations?
- Will the formation of an armor layer effect lateral erosion? And if so, how and by how much?

It is difficult to find any definitive answers to these questions and authors such as Melville and Coleman (2000), indicate that the formation of an armor layer should not be relied upon to reduce general scour depths during flood events. During a major flood the coarser bed material of the armor may be washed away, leading to the more erodible underlying material becoming exposed to the flow. Therefore it is prudent for the designer to assume that the presence of an armor layer will not limit general scour depths. However, the effect of armoring on lateral erosion accompanying any general scour may be a significant factor and at present there is no way of quantifying this effect.

2.4 Lateral erosion

The width and depth of a river channel are functions of the type of sediment and sediment load. Some authors comment that coarse sediments lead to broader and shallower rivers while fine sediments to deeper and narrower streams. Simon (1992) suggests that gravel-bed rivers will respond to disturbance primarily through lateral adjustment, whereas sand bed channels will respond through vertical adjustment.

When a river channel is subject to a change in sediment load, such as during the passage of a flood wave the channel may respond by changes to its shape, through vertical degradation and/or lateral erosion. Lateral instability may be in the form of general bank erosion, bend scour, channel widening and channel shift.

There is a high level of uncertainty in estimating how a river channel may change due to lateral instability with many concepts based on long term changes rather than changes under flood flow conditions and applying any current methods is fraught with problems.

Issues and comments about current knowledge and application of this knowledge include:

- For braided river systems there may be a migration of the main river channel or even combination of a number of flow channels into a new main channel. There is no way of predicting the river planform or any planform changes for a particular flow event.
- The approach of Maza Alvarez and Echavarria (1972) uses the concept of critical velocity so that the channel section associated with degradation undergoes widening until the average flow velocity reduces to the critical velocity. This makes the assumption that the bed and bank materials are similar and that the critical velocity of the main channel flow is the same as for material along the bank of the channel. Is this appropriate?
- What is the time scale of channel adjustment?
- Does overbank flow alter the rate of lateral erosion, and if so, how?

This last item has recently been studied by a number authors. For example, Valentine et al (2001) measured experimentally bank erosion rates for a river channel under bankfull and overbank flow conditions. They found that there was a much greater rate of channel widening once the flow was overbank than for bankfull. Pitlock, Pizzuto and Marr (2004) describe experiments looking at channel adjustment for overbank flows for flood events. They found that is was difficult to sustain overbank flows as in most of their tests the channel slowly widened, increasing the bankfull capacity until all the flow was contained within the banks. They comment that this result is consistent with theory but inconsistent with what is seen in the field. This therefore suggests our understanding channel adjustment to flood flows is incomplete.

Recent work by Doyle and Harbor (2003) attempts to model river channel profile adjustments. They note that there are three important impacts of channel widening on the degrading river section, namely:

- Channel widening will reduce the total head of the degrading reach.
- As the width of the channel increases, the rate of bed change will decrease due to a decrease in the shear stress exerted on the bed and therefore a decreased rate of erosion.
- Sediment produced by bank erosion is transported downstream and potentially contributes to downstream aggradation.

The results suggests that channels formed in fine alluvial material that is easily eroded and transported out of the system with little downstream aggradation will respond to disturbance such as vertical degradation by lateral adjustments. In contrast, if material eroded from a disturbed reach is easily deposited in downstream reaches, then upstream width adjustments are less critical to the channel recovery, thereby minimizing the degrees of channel widening.

Overall the designer has no clear method of estimating the magnitude of lateral changes that may occur to a vertically degrading river section. Until more research is undertaken the only prudent option is to assume no width adjustment occurs.

3. Prediction of bend scour

When a channel flows around a bend, secondary currents are set up and there is a change in the velocity distribution in comparison with flow in straight channels. This leads to erosion of the bed and the characteristic channel shape in bends in which the deepest flow is adjacent to the outside bank of the channel. It is believed that this shape means that during a flood there is a preferential increase in flow velocity in the deepest sections and so scour is greatest in the deepest section and exceeds the scour that would take place in a straight channel. This additional scour due to the presence of a bend is referred to as bend scour.

It is commonly assumed that bend scour is at its greatest at bankfull flows. The belief is that when the flow goes out of bank, the out of bank flow acts on the flow distribution in such a way as to reduce the lateral variation in flow velocity and so to reduce the amount of bend scour. As the depth of out of bank flow increases the amount of bend scour is expected to reduce.

Existing methods of predicting bend scour, for example Thorne and Abt (1993), are based on predicting bend scour under bankfull conditions. This provides useful information on the maximum bend scour that may occur. Bankfull flow commonly has a return period of between 2 and 3 years and the design conditions for most river crossings consider flows with significantly larger return periods. For these large return period, more information is required on how the amount of bend scour varies with the depth of out of bank flow.

Since general scour and bend scour arise from different mechanisms and bend scour is a maximum at approximately bankfull discharge, it may be inappropriate just to add together say the predicted general scour during a 200 year flood with the maximum predicted bend scour. The recommendation by some authors is that bend scour equations are not applied if the depth of flow on the floodplain exceeds 20% of the depth in the main channel. If the flow depth on the floodplain does exceed more than 20% of the depth in the main channel the bend scour will be significantly less than that predicted however further research on this issue is required.

4. Conclusions and suggestions for further research

This paper has attempted to identify the various methodologies involved in the determination of general scour and bend scour in river channels. It has been shown that there are many assumptions made in the estimation of scoured depths and each assumption can have a significant effect on the overall prediction values.

The following conclusions can be made:

- Changing flood levels can occur due to the reduction in the bed level associated with general scouring. It is difficult to accurately predict how the level will change due to problems applying the current methodology to multi-channel systems, estimating scour channel shape profiles, and what and how many cross-sections to apply the changes to.
- Longitudinal variation is difficult to account for using single cross-section methods.
- Armoring of the sediment bed will effect scour depths however there is much uncertainty as to how to quantify these effects, particular for effects on lateral erosion.
- There is a high level of uncertainty in estimating how a river may change due to lateral instability. Further research is required to development a methodology for estimating the magnitude of lateral changes that may occur due to disturbances such as vertical degradation.
- Do the current methods of predicting general scour apply to extreme flood flows?
- For large return period, out of bank flows more information is required on how the amount of bend scour varies with the depth of out of bank flow.
- It has been suggested that when estimating scour depths for large return period events it is not appropriate to combine maximum general scour and bend scour calculations.

It is hoped that the problems and ideas described here will provide current researchers with possible research ideas, with the hope that in future the prediction of general scour and bend scour depths at rivers crossing will be more reliable.

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