Reservoir hazard analysis and flood mapping for contingency planning

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SYNOPSIS. Under revisions to the Reservoirs Act 1975 introduced through the Water Act 2003, the Secretary of State has powers to direct reservoir undertakers to prepare flood plans. These are required to help the emergency services and others in providing an effective response – with regard to evacuation and other precautions – in the event of a threatened or actual dam failure, or some other uncontrolled escape of water.

This paper comments on current practice in producing flood plans to aid contingency planning in the UK, and how this may develop in the future. The paper also provides some interesting results from statistical analyses of reservoir hazard assessments, drawing from over 300 reservoir hazard analyses undertaken since 1990.

LEGISLATIVE BACKGROUND

Sections 74 to 80 of the Water Act 2003 are concerned with reservoirs and contain a number of changes to the Reservoirs Act 1975. Of relevance to this paper is Section 77, which inserts a new section into the 1975 Act that allows the Secretary of State to direct an undertaker to prepare a 'flood plan' for a large raised reservoir. The flood plan is intended to set out 'the action they would take to control or mitigate the effects of flooding likely to result from any escape of water from the reservoir'.

Although the wording in the Act is to do with controlling and mitigating the possible escape of water, the section goes on to say that the direction may (*inter alia*):

- 'specify the matters to be included in the flood plan';
- 'require the flood plan to be prepared in accordance with such methods of technical or other analysis as may be specified by the Environment Agency'; and
- require the flood plan to be provided to the Environment Agency.

Improvements in reservoir construction, operation and maintenance. Thomas Telford, London, 2006

IMPROVEMENTS IN RESERVOIRS

Part 1 of the Civil Contingencies Act 2004 sets out duties on ‘Category 1 responders’ to (*inter alia*):

- assess the risks of emergencies occurring;
- use the risks to inform contingency planning;
- put emergency plans in place;
- make information available; and
- disseminate warnings.

The Category 1 responders are those, such as the emergency services, local authorities and the Environment Agency, who are considered to be at the heart of planning for and responding to emergencies. Category 2 responders are those that would be involved in incidents that affect their sector and include such bodies as the water undertakers. It is the water companies who of course own the majority of large reservoirs in the UK, but they are defined as Category 2 responders, not because they own reservoirs that might fail and cause an emergency, but because of their infrastructure and other assets that could be affected by an emergency arising from a variety of causes.

Reservoir failure is identified as one of the risks covered by the emergency planning duties imposed by the Act. The Environment Agency’s role under the Reservoirs Act 1975 (as modified by the Water Act 2003), both as the enforcement authority for England and Wales and as the recipient of the flood plans prepared by the undertakers, dovetails neatly into its duties as a Category 1 responder under the Civil Contingencies Act 2004.

PROPOSALS FOR FLOOD PLANS

Draft proposals for the format and content of flood plans, prepared on behalf of Defra by Kellogg Brown & Root in March 2005, anticipate that the flood plan will consist of up to three elements:

1 Inundation and consequence analysis
2 On-site emergency plan
3 Draft notification to local authority of imminent dam failure

The first element is where dambreak flood inundation and potential damage mapping first appears in the flood plan, as it is used to assess the consequences of a possible dam failure and determine the appropriate ‘consequence class’ – the successor to ‘dam category’ in the ICE guide ‘Floods and reservoir safety’ (ICE 1996). Although the determination of consequence class is intended to follow the methodology in the ‘Interim guide to QRA for UK reservoirs’ (Brown & Gosden, 2004) (and, in due course, its successor document), there is no reason to suppose that inspecting engineers will not continue to exercise their judgement over whether the methodology produces an appropriate answer.

The results of the inundation and consequence analyses are also referred to in the draft notification in Part 3 of the flood plan, which it is anticipated would be required only for category A and B reservoirs. Presumably, the draft notification to the local authority will be a standing document, so that the recipient of a 'real' notification will already be familiar – before the emergency arises – with the broad contents of the notification, and will already have determined what emergency measures they would need to implement.

These proposals will have been developed further by the time that this paper is presented and will also have been discussed at the seminar at ICE on 11 July 2006, which is planned to follow the issue of the draft 'Guide to emergency planning for UK reservoirs'. However, the implications for dam failure analyses and the associated flood mapping are likely to be broadly the same as anticipated in the March 2005 inception report by KBR. In that report, KBR include among the challenges faced in the formulation of the guidance:

- the need to keep the cost of preparing and maintaining emergency plans proportionate to the reduction in risk that might be realised; and
- the need for due recognition of plans that have already been prepared.

It may therefore be expected that previously completed dambreak studies would generally be accepted as the basis for determining the consequence class and for providing the inundation mapping for flood plans for at least an interim period. In many cases, the results from these studies will be amenable to suitable digitisation and processing to convert the results to the requisite format. There could, however, be a procedure for determining the period before the next review, taking account of such matters as how recently the study was undertaken, the category of the dam, when the next Section 10 inspection is due and the timetable for a range of contingency planning in the locality.

DAMBREAK METHODOLOGY

In common with other organisations carrying out dambreak and inundation mapping, we have moved forward in the approach that we use, in response to advances in digital mapping and flood routing software, although we still normally use what is substantially the original Dambreak UK model (but not the breach module) to estimate the outflow hydrograph from the failing reservoir. For the routing of the floodwave down the valley, however, we now use either ISIS or HECRAS, as these provide facilities for interfacing with digital mapping information, using software such as 12d.

In the last decade there have also been advances in knowledge regarding the breach mechanism itself – including studies into case histories – that have led to the development of improved empirical formulae. There have also been programmes of field trials, with the purpose of calibrating breach formation models that seek to integrate the hydraulic and soil mechanics processes involved in the initiation and development of the breach (see, for example, www.impact-project.net).

In due course, the numerical modelling approach will hopefully provide the way forward for breach formation and the corresponding floodwave hydrograph. But it must be recognised that this approach is necessarily limited for dams where there is little on no information about the internal structure and material properties. In the meantime, we have, for the last few years, based the dam breach geometry and development time used in the Dambreak UK module on the empirical formulae by Froehlich (1995). These were found by Wahl (1998, 2001 and 2004) to provide the best fit when applied to a dataset of 108 dam failures.

There are also a large number of empirical methods that predict the peak outflow from simple parameters for the dam and reservoir, typically the volume (V_w) and maximum depth of water impounded (H_w) at the time that the breach is initiated. In order to act as a broad check on the dambreak results and to demonstrate the degree of uncertainty that may apply, we also, as a matter of routine, present a table that compares the peak breach outflows by a total of about 15 methods. Most of these are as quoted by Wahl (1998–2004) and two of them are of particular interest:

$$Q_p = 1.154(V_w H_w)^{0.412}$$ after MacDonald & Langridge-Monopolis (1984)

$$Q_p = 0.607 V_w^{0.295} H_w^{1.24}$$ after Froehlich (1995)

The first of these is used as part of the rapid impact assessment procedure recommended in CIRIA C542 (Hughes *et al*, 2000), and the second in the corresponding procedure in the 'Interim guide to QRA for UK reservoirs' (Brown & Gosden, 2004). Both apply to earthfill dams only. (It should be noted that the MacDonald & Langridge-Monopolis relationship is presented in graphical form in their paper, so some differences arise in its conversion to equation form by different authors.)

For the majority of UK reservoirs, where there is a fairly narrowly defined flood route downstream, a one-dimensional model is sufficient and appropriate for dambreak modelling. In some cases, there are 2D effects that have to be taken into account in the interpretation of the results, that is in the process of transposing the 1D modelling results into the requisite inundation and damage plans. But there are cases where this is unlikely to be adequate, such as reservoirs whose failure would results in very wide areas of inundation, or where there is the likelihood of separate flood paths being formed following different routes. In these situations, two-dimensional (depth-integrated) modelling would normally be the appropriate choice. As the floodwave routing and mapping software develop, it is inevitable that increasing use will be made of 2D analyses, and these can be expected to become more commonplace over the next decade.

We would suggest that flood plans and the associated inundation maps be reviewed at the time of the Section 10 inspections and perhaps at more frequent intervals if significant changes are suspected. These reviews would examine whether any changes have occurred downstream of the dam in terms of flow routes and land use, but would not be expected to involve repeating the analyses, unless significant changes are found or there has been a recognised advance in the accuracy of the analysis method since the flood plan was prepared.

STATISTICAL ANALYSES

In their paper at the Bath conference, Tarrant and Rowland (2000) presented a number of anonymous case studies, together with a series of graphs which attempted to establish if a simple correlation could be devised between the basic reservoir characteristics (dam height and storage capacity), the characteristics of the downstream valley (gradient and shape) and the extent of total property destruction and partial structural damage. Such a relationship could be useful in the planning and competitive bidding for these studies, particularly in cases for which there is no obvious downstream boundary, such as the sea, but might also provide a useful screening tool for deciding whether a detailed dambreak study is required.

The best of the simple correlations, for reservoirs with a capacity of at least 1×10^6 m^3, was between dam height and the extent of partial structural damage, but this treatment still left a wide range of results and the authors concluded that the relationship was 'tenuous'. They went on to conclude that the extent of damage and inundation can only be determined by a full dambreak assessment, but that the simple relationship could be useful for planning the extent of the dambreak model required.

For this paper we have updated the statistical analyses carried out in 2000, and have also widened the compass to include reservoirs in our dataset with a capacity greater than 0.5×10^6 m^3, so that a total dataset of over 100 embankment dams was used. For the same dataset we have also tabulated the relationships between the peak dambreak outflows determined in our detailed dambreak studies and the peak outflows determined by the two empirical methods referred to above.

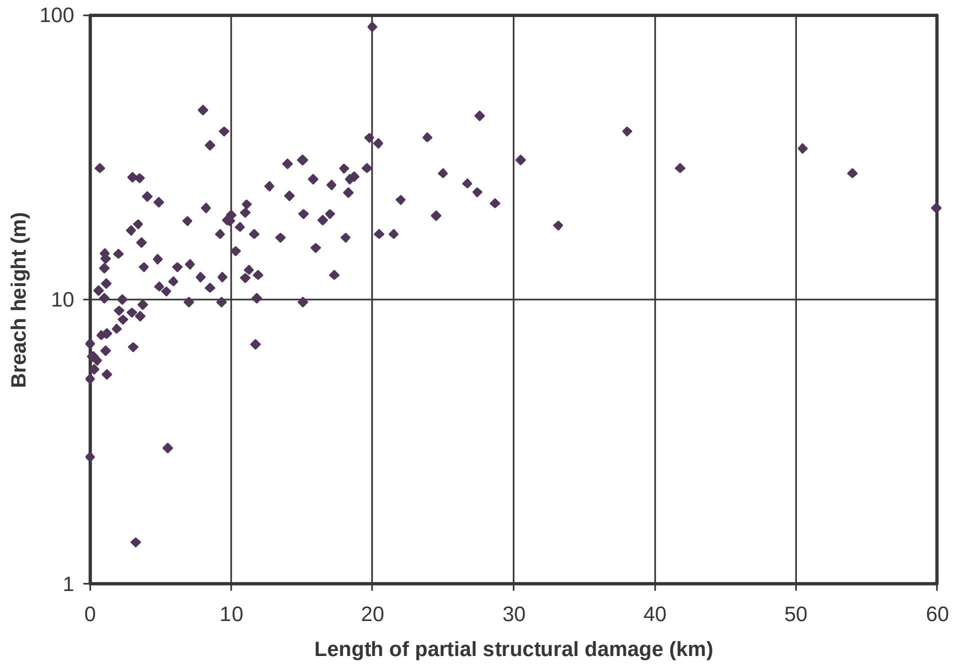

Figure 1. Damage length as a function of breach height for over 100 dams

Figure 1 shows the best of the previously tested relationships, that is between the breach height and the length of partial structural damage, updated to include the current dataset. We experimented with a number of alternative formulations, involving various combinations of dam height and reservoir capacity and found no noticeable improvement over this relationship. As may be noted, there is a great deal of scatter in these results, even with the breach height plotted to a logarithmic scale.

Figure 2 shows the relationship between the peak reservoir outflow determined in over 100 detailed dambreak studies with those estimated using the empirical peak flow relationships suggested by MacDonald & Langridge-Monopolis (1984) and by Froehlich (1995). The empirical relationships are expressed as the ratios to the outflows determined in the detailed studies and it should be noted that they are plotted in log-log form.

What is immediately apparent in Figure 2 is the wide variation in the values obtained from the empirical formulae, encompassing a band of between about one tenth and seven times the value determined in the detailed study. Of course, some of the variation must be due to inaccuracies inherent in the breach geometry and timing parameters that were employed in the detailed analyses, and to the fact that a number of incremental changes have been made to the approach over a period of more than 15 years. It is also clear that there is a distinct trend for both of these empirical methods to over-estimate the discharge for the cases with smaller breach outflows and to under-estimate the larger discharges. This is perhaps fortuitous, as the rapid approach in the 'Interim guide' (Brown & Gosden, 2004) is likely to be applied to the smaller reservoirs, with a full dambreak study being most common for the larger reservoirs. Although both empirical flow estimation methods, on average, produce results that are similar to those from detailed studies, the Froehlich (1995) equation exhibits a lesser spread than the MacDonald & Langridge-Monopolis (1984) equation. This tends to support the adoption of the Froehlich equation for the 'Interim guide'.

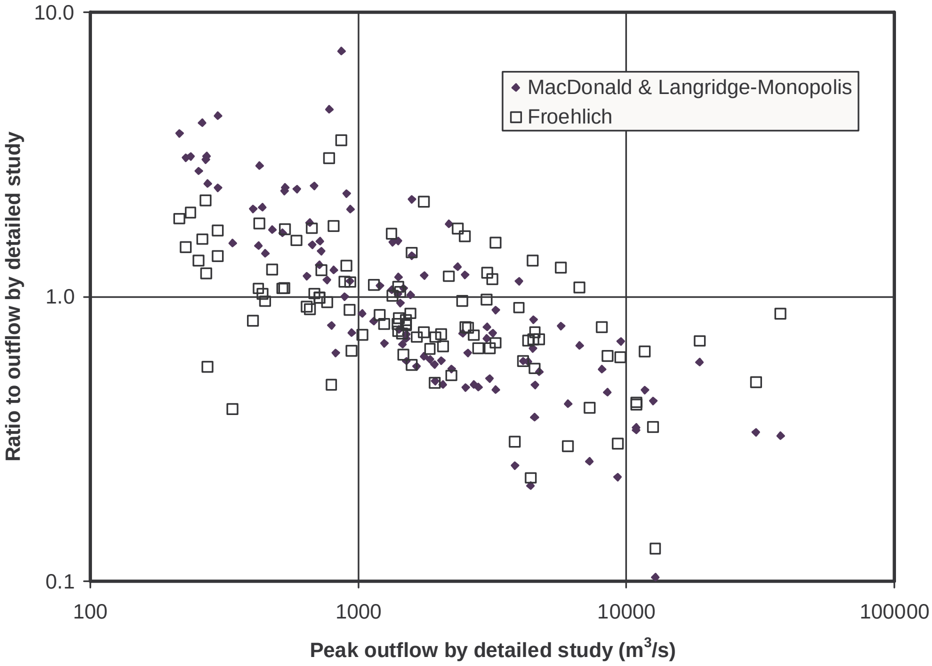

Figure 2. Comparison of empirical peak flows with those from detailed dambreak study

We have also attempted to find a correlation between the average bed slope of the downstream flowpath and the 'attenuation length scale' (L_a), as used in CIRIA C542 (Hughes et al, 2000) and the 'Interim guide'. The attenuation length scale is the distance over which the peak discharge of the floodwave falls to 37% of the dam breach peak outflow. Again, such a relationship would be of use when planning the extent to which the downstream flowpath must be modelled. Figure 3 shows the relationship between bed slope and L_a for 20 dams with breach outflows between about 100 and 30 000 m^3/s.

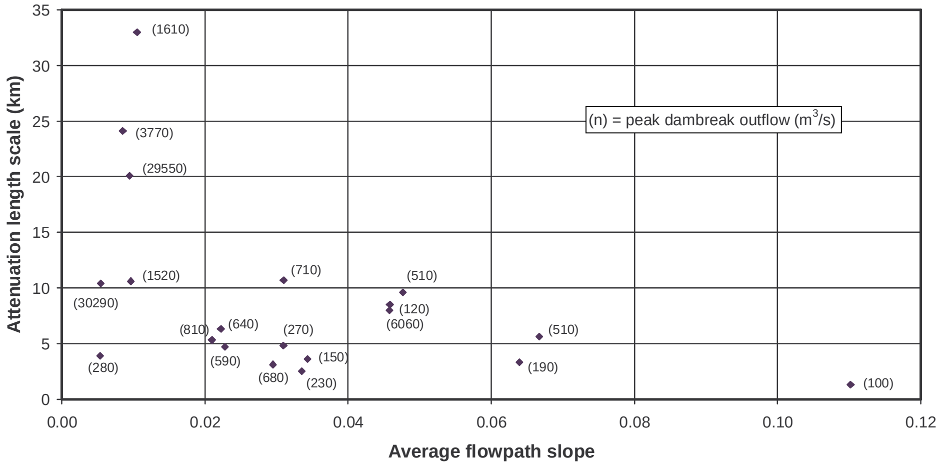

Figure 3 Relationship between L_a and average downstream slope

Again, there is a large scatter of results, with dam breaches of a similar size and average flowpath gradient having very different attenuation rates. This is because other factors – such as the width of the floodplain, the presence of obstructions to the floodwave and the resulting volume of available floodplain storage – also have an influence on the attenuation rate. There is a tendency for the larger dam breach floods to attenuate over a longer length than the smaller breach floods, which is no surprise, because the larger the flood, the more quickly the floodplain storage is exhausted, so that a larger proportion of the flow must continue downstream.

Although the results in Figure 3 do not appear to offer a useable correlation for general application, they can be referred to for additional guidance. Further investigations, involving the analysis of a larger number of case studies, together with consideration of different combinations of parameters, might lead to the development of a improved empirical approaches to assist in the planning of reservoir hazard analyses.

CONCLUSIONS

The new provisions for ‘flood plans’ in the Reservoirs Act 1975 (added by the Water Act 2003), together with the requirements of the Civil Contingencies Act 2004, create an impetus for improving and standardising approaches to dambreak modelling, inundation and consequence mapping in the UK. In order to maintain and enhance standards, it must be recognised that, where new studies are required, they must be carried out over a period of some years, taking account of such factors as the category of the dam, when the next Section 10 inspection is due and the timetable for developing contingency planning for a range of risks in the locality.

A key issue is how the dam industry presents the uncertainties to the emergency planners. We would support the adoption of some standard assumptions to obtain consistency between the analyses by different reservoir owners and consultants, recognising of course that these may vary in the future as efforts are made to obtain a closer representation of reality. The Impact research (www.impact-project.net) has provided some more data towards improving understanding in the subject, and there is clearly scope for providing standardised guidance for older reservoirs where little is known about their construction. Nevertheless, the preparation of flood plans should not be divorced from the requirement for dams to be assessed individually by experienced dam engineers.

A pragmatic approach should be adopted with regard to the large number of reservoirs for which dambreak studies have already been undertaken – some of them over 15 years ago – accepting that differences in approach and presentation from the current 'ideal' do not necessarily require the studies to be repeated in their entirety.

This paper presents the results of limited statistic analyses of flood damage lengths and the rate of floodwave attenuation in relation to simple parameters concerned with the reservoir and its setting. Nevertheless, it remains the case that there is 'no simple solution' (Tarrant & Rowland, 2000) to the question of how to relate the distance over which the peak breach outflow attenuates, or the extent of damage, to simple parameters such as the reservoir volume, dam height and stream gradient. Analysis of a wider range of parameter combinations and a greater number of case studies could lead to the development of an empirical formula for use during the planning of future dam failure impact assessments.

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