The influence of infrastructure embankments on the consequences of dam failure

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SYNOPSIS. Dam break inundation mapping is the first part of the assessment of the consequences of failure of a dam. Although there has been significant expenditure on research on the breach hydrograph, there has been little attention given to the influence of infrastructure embankments across the inundated area on flow paths, depth of inundation and consequences. This paper discusses the general issues and provides two case histories where the consequences of dam failure are significantly influenced by major infrastructure embankments across the valley downstream of the dam.

INTRODUCTION

Estimation of the consequences of failure of a dam is necessary for two reasons

a) to estimate the extent of flooding and population at risk (PAR) for use in planning evacuation in the event of a failure, and
b) where a risk based approach to dam safety is used, to provide the likely loss of life (LLOL) and property damage to allow the dam owner to determine whether the risk has been reduced to as low as reasonably practicable (www.hse.gov.uk/risk/theory/alarp.htm)

The first step in a consequence assessment is dam break inundation analysis and mapping. This is an evolving process with initial Defra sponsored research into the methodology being published by Binnie and Partners (1986, 1991) and a summary of early analysis in UK being given in Tarrant et al (1994). Subsequent research into extreme flood processes has largely focused on breach discharge and propagation of the flood wave down the valley (Morris & Hassan, 2004, www.floodsite.net).

One area that has received little attention is the influence of infrastructure embankments across the downstream valley on the consequences of failure. To simplify the analyses, many existing dambreak analysis have assumed that downstream transportation embankments are breached under the dambreak flood, and have therefore modelled the embankments as having pre-existing notches. Although this is conservative in terms of maximizing the flow passing downstream, it neglects additional backing up of water upstream of the transportation embankment should it not breach immediately. This paper discusses the general issues and presents two case histories of full inundation analysis where major infrastructure embankments across the valley significantly influence the consequences of failure.

GENERAL ISSUES

As with any analysis the quality of the output depends on the quality of data used, method of analysis and reasonableness of assumptions made. The important assumptions will vary depending on what is considered to be the critical output, namely the

a) areal extent of flooding,
b) likelihood of structural damage to property, or
c) risk to people who are in the open in the inundated area.

The first of these is considered to be the primary measure of potential consequences of failure, as it defines the area to be evacuated and number of properties in which people are likely to be at some risk. It has been found that the width of flooding near the dam is relatively insensitive to peak flow: typically the base of the valley is completely inundated and the valley sides are much steeper than the cross fall on the valley floor. Once the dambreak flow has travelled downstream into wide valleys where the flow is less deep then the width of flooding becomes more sensitive to peak flow, but here the risk to people may be reduced.

Table 1 summarises some of the key issues that will affect the extent of flooding due to a dam failure. Issue 1 is well covered elsewhere. The other issues are equally important but have received less attention, with this paper focussing on Issue 2a. Table 2 summarises some of the main factors affecting the impact on people.

Table 1: Key issues affecting extent of dam break inundation

Issue	Key factors affecting estimate
1. Breach formation and discharge hydrograph	Mode of initiation and progression of breach Zoning and properties of embankment fills, Crest width and surfacing, Dam height and reservoir capacity, Magnitude of inflows into reservoir
2. Attenuation of flood wave down valley	*a) Infrastructure embankments across valley:* Height of embankment; Size of openings in embankment, vulnerability to blockage; Vulnerability of openings to piping/scour failure leading to breach of embankment when water impounded.
	b) Degree of damage to buildings: Totally demolished or remain structurally intact; types of wall construction.
	c) Other factors: Hydraulic roughness; Erosion/deposition of sediment and debris during flood; Natural inflows Resolution and accuracy of topographic survey
3. Distance downstream at which dambreak analysis may be terminated	Extent to which valley widens out and catchment increases; Volume of reservoir and time to failure; Longitudinal gradient of valley, and thus whether celerity effects mean the flood travels as a catastrophic wave

Table 2: Key issues affecting impact of dam break flood on people

Issue	Comments
1. Integrity of buildings, and thus risk to occupants above the flood level	Dependent on form of building construction. Binnie and Partners (1986) suggest total destruction where vd > $7m^2/s$, and inundation only where vd< $3m^2/s$ with partial damage between these values
2. Number of people on transportation routes, or in open	This will vary with time. There is little data or guidance on which estimates may be based
3. Fatality rate (percentage of those in the inundated area that are likely to be killed)	This will vary across the flood plain, with warning time and time of day. A simplified approach using a single fatality rate for a reach of the valley is given in the Interim Guide to Quantitative Risk Assessment (Brown & Gosden, 2004)

TRANSPORTATION EMBANKMENTS

Transportation embankments across the flood plain may act as secondary dams. Where these structures are small in relation to the dam height, or are likely to be breached early in the flood, this effect may be insignificant. However there are situations in which they could significantly influence the extent of dambreak inundation and the risk to people.

The actual behaviour of transportation embankments while the dam break flood wave is passing will be complex. It will vary with time and may potentially include failure by overtopping, piping along the structure interface or scour at the downstream side of the structure. Depending on the timing of any such failure relative to the passage of the dam break flood, consequential breach of an infrastructure embankment could produce a further flood wave. The impact of such secondary events on emergency services and survivors from the initial flood wave could be particularly distressing.

Table 3 summarises the possible scenarios for the effect of transportation embankments on dam break flow. Where an embankment breaches this may lead to higher flows downstream, which in turn makes it more likely that transportation embankments further downstream would themselves fail. Thus overall there are a significant number of possible scenarios, depending both on the behaviour of individual embankments and the likelihood that the failure of any one embankment influences the probability of failure of any other.

Assessment of the risk to those in the potential inundation area is further complicated by the location of the population at risk:

a) upstream of an embankment, the number of people at risk is maximised if the embankment remains intact, as this maximises the flood depth, though the fatality rate could be lower because of reduced velocity;
b) downstream of an embankment, the risk to life is maximised if the embankment breaches at an early stage in the dam break flood because attenuation of the flood wave is minimised, leading to greater depths and velocities.

Table 3: Possible scenarios for the effect of transportation embankments on the extent of inundation

Response of transportation embankment to dam break flood	
Intact	Breached by dam break flood
Effect upstream of embankment	
Increased inundation upstream (water level backed up as determined by the size of culvert opening, the degree and timing of blockage and the height of embankment) but reduced velocity	Two stages of behaviour: a) Increasing inundation, limited to the overtopping depth necessary to breach the embankment b) After the breach, the upstream water levels will be governed by the breach dimensions; where the breach is wide, the control may change to the valley cross-section and slope
Effect downstream of embankment	
Peak flows attenuated by storage upstream of transportation embankment	Several phases a) Flow attenuated to capacity of openings b) Dam break wave from breach of the embankment c) Breach dimensions govern flow through breach, and thus downstream depths and velocities, when fully developed may be governed by the valley cross-section and bed slope

CASE HISTORY A : FLOOD BREACHES INFRASTRUCTURE

Case History A was a dambreak analysis recently carried out by Jacobs of a 24m high dam retaining a 1.3Mm^3 capacity reservoir. The analysis was run in an InfoWorks RS model built for the dam break analysis, with two scenarios analysed as shown in Table 4. There were no scenarios modelled with alternative combinations of breached and non-breached embankments. Breach discharge of the dam was estimated as 1800m^3/s, with a time to peak of around 20 minutes and an overall duration of about 40 minutes. The dam break flood was estimated to reduce to the natural 1% annual probability fluvial flood about 19km downstream, where the dam break model was terminated.

The sequence of modelling was an initial rapid impact assessment using the Interim Guide to QRA to determine screening level parameters, followed by a reconnaissance visit to the river valley prior to the detailed modelling. Although a detailed hydraulic model of the river channel was available for the immediate area downstream of the reservoir, it was only suitable for fluvial flooding as it did not include details of all the structures on the valley floor which would influence dam break floods. Crest elevations for infrastructure embankments were obtained directly from ground model data, whilst dimensions of openings not on the line of the main watercourse were measured during the site visit.

Table 4: Scenarios considered in breach analysis for Case History A

Scenario	Assumption	Comment
Intact	All infrastructure embankments intact	Provides an indication of the likelihood of failure of each structure from overtopping together with a maximum impounded water level behind each structure
Breached	All structures that are assessed as likely to breach fail instantaneously at the beginning of the simulation.	Provides an evaluation of the maximum effect of peak breach flow down the valley

Address Point data was used to give direct counts of the number of properties at risk from the breach inundation extent. The cost of damage to property was also estimated for the dam breach event and required the floor area of non-residential properties, which were manually measured using GIS. This proved to be time consuming and it is recommended that data on commercial property values and areas, as included in the National Property Database (developed for the Environment Agency), is obtained to streamline the process whenever possible.

The paper focuses on a railway embankment located 300m downstream of the reservoir, just downstream of the confluence of the impounded watercourse with a major river, and the effect of this on flood flows in the first 6km downstream. The railway is the first major hydraulic obstruction affecting the attenuation of the flood wave down the valley, and is assumed to breach in the “breached” scenario.

The railway embankment crest is approximately 8m above the surrounding floodplain. The crest width is 10m and the base width is 40m. There are four openings through the embankment, details of which are provided in Table 5. Figure 1 shows one of these openings, where a road is spanned by a cast iron bridge.

The likelihood of openings through the embankment being blocked was assessed in accordance with Table 3.4 of the draft Guide to Emergency Planning (Jacobs, 2006). This considers the minimum opening dimension and provides estimates of blockage at constricting structures in a dam break scenario. The effective open area is a product of the blockage assessment.

Table 5: Openings in the railway embankment

	Bottom width (m)	Height of crown (m)	Open area (m^2)	% blockage	Effective open area (m^2)
Culvert	10.0	1.7	11	50%	5.5
Road 1	4.5	5.0	15	80%	3.0
Road 2	12.7	7.9	70	50%	35.0
Road 3	7.6	7.1	30	80%	6.0

Likely breach dimensions for transportation embankments were determined using Froehlich (1995), and were assessed for this railway embankment as 30m base width and 45m width at the embankment crest and assumed to be additional to the existing openings. This would require removal of about 8000m^3 of fill. Comment on the need for research into breach dimensions in infrastructure embankments is given in section on debatable issues.

It was assessed as likely to breach on the basis of the fill being relatively loose as it was originally placed without modern compaction equipment and a 0.5m depth of overtopping, together with non-uniformity of crest levels leading to concentrated flow. The 10m crest width, and the good condition of the structures at the various openings, will however tend to prolong the period before full breach occurs.

Figure 2 presents a plan view and the inundation extent upstream of the embankment for the two scenarios in Table 4 (embankment intact and breached) whilst Figure 3 illustrates the peak flood levels down the river valley for the two scenarios. Table 6 summarises the change in flood depths and flow after failure of the embankment.
Key conclusions from this analysis regarding the effect of the transportation embankment are that if it does not breach:

a) Flooding backs up into the adjacent valley
b) Upstream water depth increases by 50%
c) Potential reduction in water level and fatality rate downstream, due to attenuation.

Table 6: Effect of transportation embankment on dam break inundation

Scenario (as Table 4)	Upstream of embankment			Downstream of embankment		
	Depth just upstream (m)	Flooded width[1] (m)	Properties flooded	Velocity. (m/s)	Discharge/ width (m^2/s)	Fatality rate (%)
Breached	9.0	180	255	1.7	7.9	3.0
Intact	13.5	195	327	1.5	7.3	2.7
Difference %	50%	8%	28%	-12%	-8%	-10%

Note: Width across valley at distance u/s of 2 x flooded width

Figure 1: Case History A - Bridge opening through railway embankment

CASE HISTORY B: FLOOD RETAINED BY INFRASTRUCTURE

Case History B is a situation where the transportation embankment is so high that it can retain the complete dam breach discharge without failing, thereby significantly reducing dam break flood flows downstream but increasing water depth upstream of the embankment. The dam break analysis was performed using DAMBRK.UK in the 1980s' and recently reviewed.

The dam which is considered in the analysis is 28m high and retains a 0.8Mm^3 capacity reservoir. The breach discharge is estimated as 1000m^3/s with a time to peak of just under 20 minutes. About 2.5km downstream of the dam a modern road passes across the valley on a 10m high embankment, as shown in Figure 4. The only openings are two 2.7m diameter corrugated steel culverts. This embankment could retain 1.5Mm^3 without overtopping and was considered as a potential Environment Agency flood storage site. The plan extent of dam break flooding with an intact and breached embankment is shown on Figure 5. There is a railway crossing just upstream, and although it would complicate flow conditions, it would be drowned out by water backing up from the much larger road embankment.

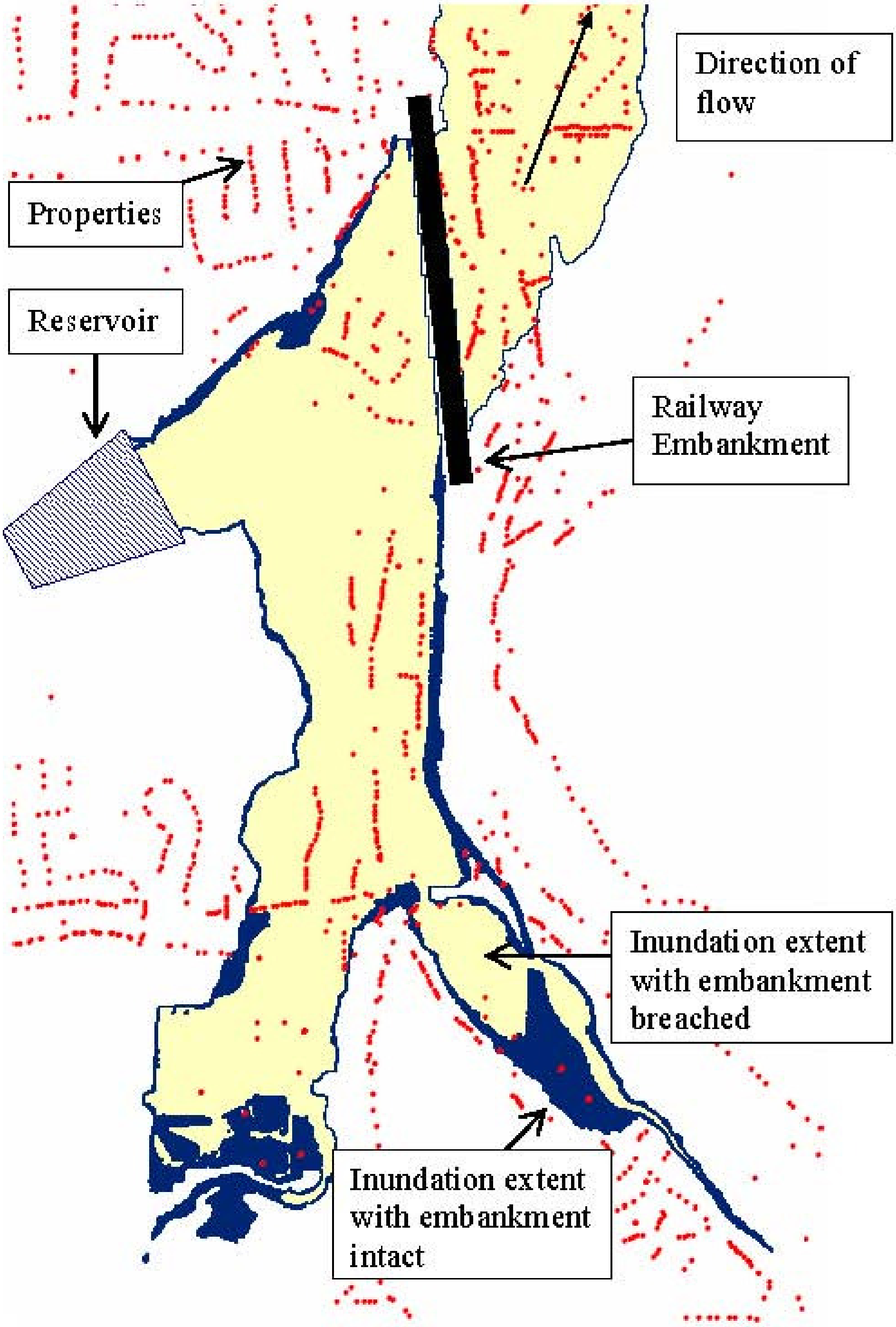

Figure 2: Case History A - Extent of dam breach inundation

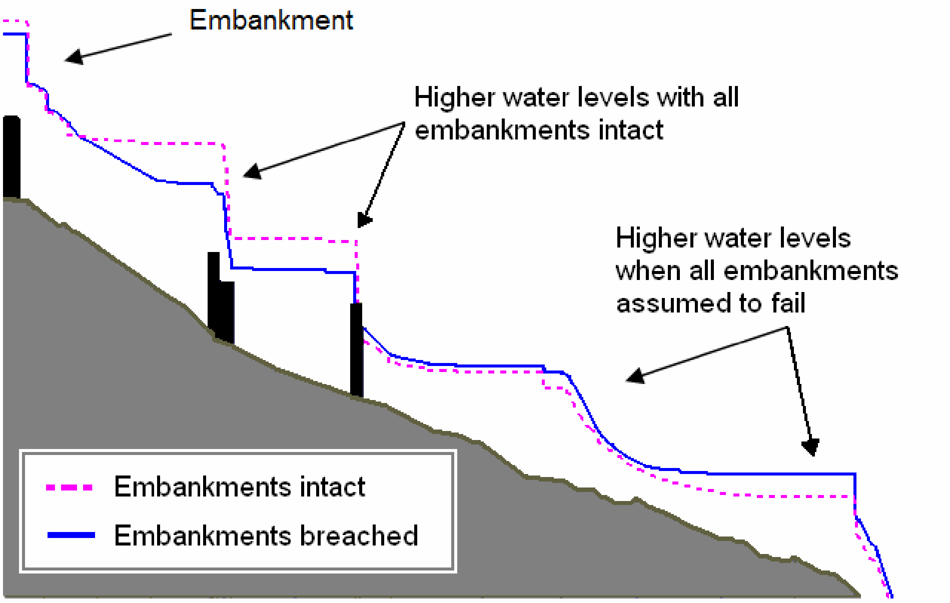

Figure 3: Case History A - Long section down river valley

There are small towns just upstream and downstream of the road embankment, with populations at risk in the breach scenario of 200 and 1600, respectively. The river is culverted through part of the town downstream. When the effect of the transportation embankment is taken into account the number of people at risk upstream will more than double, whilst that downstream would effectively reduce to zero.

The significant findings from considering the road embankment are

a) The entire storage in the reservoir could be retained upstream of the road embankment so that in a "sunny day" failure scenario there would be no major flooding in the town downstream
b) In a rainy day scenario, the embankment could be overtopped but breaching by overtopping would require prolonged overtopping to cut through the substantial crest width and tarmac road. Failure may alternatively occur at lower flows by piping or scour along the road culvert
c) In both cases the peak flood depth upstream of the road embankment would be up to 10m, compared to the 2.5m depth shown on the current maps. This would approximately double the number of houses flooded in the village upstream of the dam and significantly increase the extent of the area to be evacuated
d) Floodwater would back up a side valley parallel to the road, which includes isolated houses that are unlikely to be aware of their risk

Table 7: Effect of transportation embankment on dam break inundation

Scenario (as Table 4)	Upstream of embankment		Peak flow downstream of embankment (m^3/s)	Total population at risk (u/s and d/s)
	Depth just upstream (m)	Flooded width[1] (m)		
Breached	2.5	70	900	1800
Intact	10	240	90	450
Difference %	400%	340%	-90%	-75%

Note: Width across valley at distance u/s of 2 x flooded width (breached)

Figure 4 Crest of road embankment (Case History B) from left abutment

DEBATABLE ISSUES

What allowance should be made for infrastructure embankments in dam break analysis?

It is clear that transportation embankments can have a significant effect on the extent of flooding in the event of dam break, and thus on the location and magnitude of the population at risk and likely loss of life. It is also clear that the actual behaviour in the event of dam failure is likely to be complex, and thus difficult to predict accurately, particularly where there are several embankments in the downstream valley. It is suggested that the approach set out in Table 4 provides a good initial approach to bracket the potential range of behaviour. In some cases, for example where there is only one major centre of population downstream, it may then be appropriate to carry out a further analysis with the likely worst case for that population. This could be done using the assumption that all upstream transportation embankments are breached, but that those just downstream are not breached.

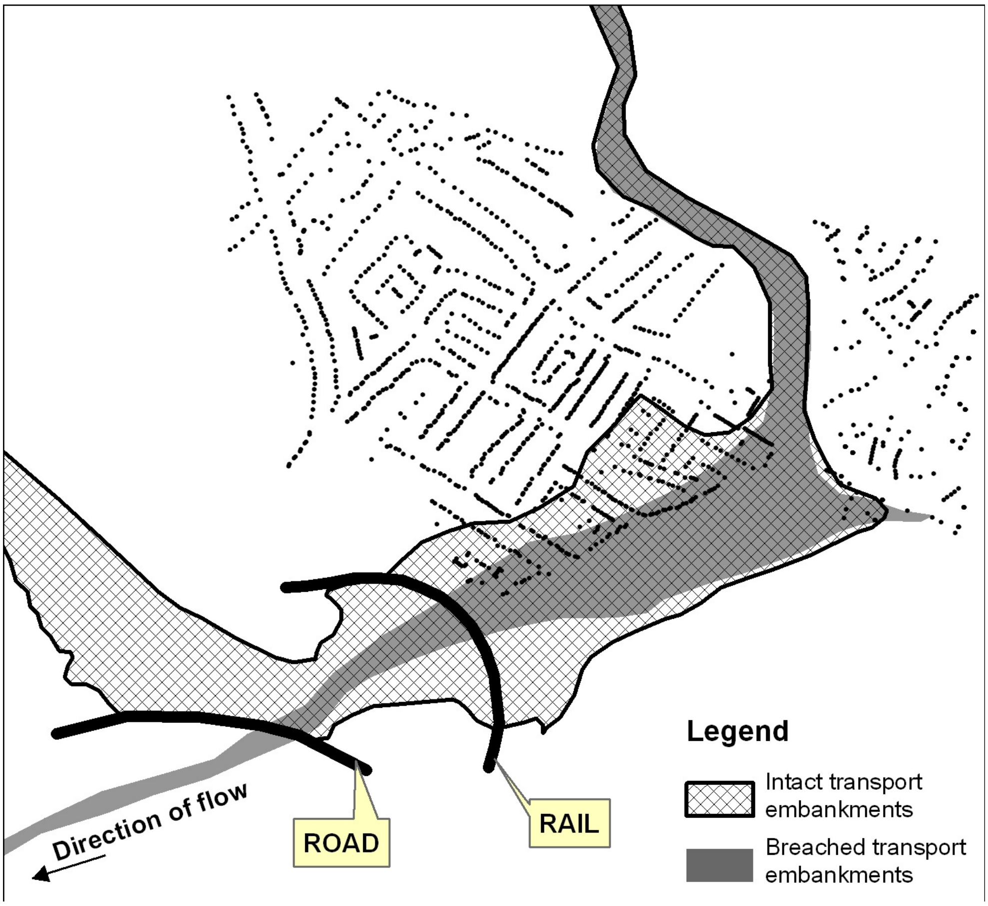

Figure 5: Case History B - Dam breach inundation extents

<u>How should breach of transportation embankments be modelled?</u>
The main issue is whether a transportation embankment would breach, with a secondary being how it would breach; whether by overtopping, or at the edges of existing openings through the embankments (e.g. Figure 1 and Table 5). It is also likely that existing methods for predicting initiation, rate of breach formation and final dimensions are not suitable for transportation embankments. It is suggested that further research is required into methods for prediction of the conditions of when breach of transportation embankments is likely to occur under dam break loading.

<u>Where multiple scenarios of flow condition are analysed, which scenario should be used to estimate likely loss of life?</u>
Techniques currently available for estimating the likely loss of life arising from dam failure include

a) Figure 9.1 of Interim Guide to QRA (2004), which is relatively simplistic, using averaged fatality rates inferred from previous incidents

b) Defra R&D project report FD2321 (2006) which requires knowledge of flood depth and velocity varying spatially with distance from the river, and also the percentages of very old and disabled or infirm in each sub-area

To obtain estimates of velocity varying spatially normal to the direction of flow requires 2D flood modelling which is not always available, and requires higher quality ground data to produce reliable results. The former has the significant benefit of simplicity, but introduces uncertainties where there are several dam break scenarios as to which set of flow parameters are used to estimate the fatality rate. Case History A conservatively used the velocities with breached embankments in combination with maximum depth. Initial fatality rates may not be the sole driver for emergency services: large areas of potential inundation affecting many people could be seen as a higher priority than small numbers of lives at risk in isolated areas since deaths from the secondary effects of flooding – exposure, infection – could be just as big a concern.

PRACTICAL IMPLICATIONS FOR DAM BREAK IMPACT ANALYSIS

The case histories presented depend on good quality data to make meaningful estimates of the consequences of failure. This includes

a) topography of the valley downstream from the dam
b) for transportation embankments and other structures crossing the valley,
    - the crest level (to allow an assessment of the depth and location of overtopping) – from Lidar data
    - the size and construction of openings through the structures
    - other information necessary to asses the likelihood of being breached
c) data on properties at risk should include floor area in non-residential property (e.g. as given in National Property Database)

Items ‘a’, the Lidar data in ‘b’ and ‘c’ are, subject to licensing issues, available from the Environment Agency. They would be expensive if they had to be purchased in the open market. Item ‘c’ is not normally readily available, and is most easily obtained by on-site survey which can be carried out to sufficient accuracy with hand-held laser “tapes”. This is not possible where there is no public access but approximate assessments can be made from aerial photographs and mapping. The other alternative is asking the owner of the infrastructure for the dimensions of clear openings in his infrastructure, but this is likely to be time consuming. There could be benefit in a national database of data on infrastructure embankments relevant to dam breach analyses.

CONCLUSIONS

The prediction of the extent of dam break flooding, and its consequential impact on people, is inevitably subject to significant uncertainties including:

a) the speed of failure of the dam, and thus the magnitude of the peak breach outflow
b) infrastructure embankments across the valley downstream which can act as secondary dams attenuating the peak dambreak flow but causing additional flooding upstream, whilst subsequently failing causing secondary flood waves
c) the fatality rate, which will vary with time of day, vulnerability of the population and effectiveness of emergency planning, including effective warning
d) the quality of data used in making the above assessments

This means that any dambreak should only be considered as indicative, with effort put into defining the upper and a lower bound extent of flooding, rather than any single "correct" answer.

It is noted that in many situations the width of flooding near the dam is relatively insensitive to breach discharge and the presence of transportation embankments. This is because where the base of the valley is completely inundated, the sides of the valley are much steeper than the cross fall on the valley floor. However, changes in breach discharge and transportation embankments will have a greater impact on the risk to people and fatality rate, which are a function of depth and velocity.

This paper has examined the effect of transportation embankments downstream of dams and shown how the assumptions made have a significant affect on the consequences of dam failure. In the extreme they may store the dambreak flood, and effectively prevent flooding downstream. On the other hand they may be overtopped and fail, causing a secondary flood wave with major implications for emergency services and recovery operations.

It is recommended that all dam break analysis should catalogue and give site specific screening level consideration to infrastructure embankments in the valley downstream. The rapid dambreak method given in the Interim Guide to QRA has been extended to facilitate this. The screening assessment should then include the potential effect of downstream embankments on the quantitative estimate of the consequences of failure, of which the population at risk and likely loss of life are the key outputs. The outputs from the screening assessment may be used to determine how the transportation embankment should be included in a hydraulic model. It is suggested that in most situations the approach set out in Table 4 would be appropriate.

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