Dunalastair Dam – Interaction of Risk Assessment and Emergency Response Plan.

A. C. MORISON, Halcrow Group, Swindon, UK
S. J. KING, Scottish and Southern Energy, Perth, UK

SYNOPSIS. Dunalastair Dam is a concrete gravity dam built in 1933 incorporating vertical spillway gates to divert flows into the Tummel Aqueduct for Tummel Power Station. Stability assessment shows that the dam is stable up to the 1:10,000 year return period flood, but that larger flows could cause failure of the dam. Dunalastair Dam is Category A, with the village of Tummel Bridge at risk. Dambreak analyses show that failure at PMF of Dunalastair Dam would inundate Tummel Bridge village to a depth of up to 5.9m, but that this would not cause much more damage than the PMF alone. To increase the spillway capacity to pass the PMF would require a complete re-build of the dam. QRA assessment indicates that risks should be mitigated. Flooding in Tummel Bridge commences at about the 1:100 year flow, and becomes widespread between the 1:1,000 and 1:10,000 year events. Scottish and Southern Energy (SSE) is well placed to predict flood conditions leading to extreme floods before the situation becomes imminent. It is anticipated that the limited population of Tummel Bridge could and would be evacuated to safety before the critical 1:10,000 year flood peak is reached, and that evacuation significantly mitigates the consequences of dam failure. An emergency response plan for evacuation of Tummel Bridge is currently being developed to provide flood risk mitigation.

DESCRIPTION OF THE DAM

Dunalastair Dam is located on the middle reaches of the River Tummel about 20km west of Pitlochry in Perth & Kinross Region of Scotland. Upstream of Dunalastair the total catchment area is 697km² of mountainous terrain, extensively developed for hydropower. Of this, 291km² is indirect catchment and 646km² is upstream of Loch Rannoch, the outflow from which is controlled by a gated weir operated by SSE. There are a number of reservoirs and natural lochs in the catchment, of which Loch Ericht and Loch Rannoch act as major storages. Dunalastair Dam acts as a head pond and diversion weir on the River Tummel to divert flow into the Tummel Aqueduct, a contour headrace aqueduct leading to Tummel Power Station.

Dunalastair Dam is a complex gated concrete structure up to about 11m high and 88m long on a rock foundation within the original river channel. It retains 2.3 Mm^3. The dam was completed in 1933 and consists of:

- The gate structure with two vertical lift gates each 25ft (7.6m) square operated by hoist from a high level bridge between the gate piers
- A gravity ogee overflow spillway section 21.7m long in three bays beneath a footbridge, discharging to a concrete and rock apron
- Four steel lined gravity siphons in gravity sections
- Twin intake gates to the 4km long Tummel Aqueduct, which is considered as a separate large raised reservoir
- A multi-pool fish pass structure on the dam left abutment
- Various intermediate and abutment gravity sections and walls

Details of these are shown on original as-constructed drawings held by SSE. Figure 1 below shows a view of the dam.

Figure 1. Dunalastair Dam

DAM CATEGORY AND RECOMMENDED FLOOD STANDARD

The dam was inspected in 2003 by Mr A Macdonald [1]. The dam was classified as Category A, minimum standard, for which "Floods and Reservoir Safety. 3rd Edition" [2] requires the dam structure to be stable up to the PMF water level. The report includes a recommendation for a structural assessment of the flood gates and control structure and an assessment of the stability of the overflow section.

DESIGN FLOODS

A number of hydrological assessments have been made of the complex cascade forming the catchment. Flows depend particularly on snowmelt and gate operating assumptions. The current assessment is based on a winter PMF with 500mm of snow cover, 3mm/hr snowmelt and current operating rules for flood conditions. The design PMF has a peak outflow from Dunalastair (assuming no dam failure) of 2,525m^3/s and a peak water level upstream of Dunalastair Dam of 205.5m aOD. This is about 5.2m above dam crest (parapet) level and 5.5m above original design water level.

The structural assessment carried out in November 2007 [3] adopted a 1:10,000 year return period FSR [4] assessment prepared for a previous statutory inspection. Peak water level from this was about 199.4m with an outflow of 775m^3/s, which is within the original design conditions.

Revised 1:100, 1: 1,000 and 1:10,000 year flood assessments using the FEH [5] method have recently been carried out for flood mapping in Tummel Bridge. With 3mm/hr snowmelt, the 1:10,000 year flood has a peak outflow of 1,191m^3/s and a peak upstream water level of 201.955m aOD, which is significantly higher than the previously derived FSR level. However the FEH extrapolation to 1:10,000 years remains questionable and this has not been adopted for structural assessment.

DAMBREAK IMPACTS

A dambreak and consequence study was carried out for the Tummel dams in 2003 [6&7]. The results relating to Dunalastair are summarised below.

About 5.5 km downstream of Dunalastair dam, the River Tummel enters Loch Tummel, retained by Clunie Dam. A breach of Dunalastair Dam would raise the water level of Loch Tummel by about 0.3m and Clunie Dam has recently been anchored to withstand the PMF. It is therefore anticipated that failure of Dunalastair Dam would not result in a cascade failure of Clunie Dam. The area at risk is therefore the Tummel valley between Dunalastair Dam and Loch Tummel. The Tummel valley immediately downstream of the dam includes a few isolated properties, but the critical area at risk downstream is the village of Tummel Bridge.

Tummel Bridge is a modest village with about 60 residential properties. In addition there are a few community buildings, a hotel and a large caravan/holiday park. Infrastructure in the valley includes minor but strategic roads and bridges, two SSE power stations, an SSE depot and a significant HV switching station. The total population at risk has been estimated as about 350, 150 of whom are from the holiday park. This seems to be an upper bound estimate, and will be significantly lower in winter.

Initial dambreak modelling, with failure assumed to occur simultaneously with the peak PMF water level, estimated a worst case PMF dambreak peak flow of 5,380m³/s immediately downstream of the dam,. This attenuates to 3,778m³/s at Tummel Bridge, with an over-bank depth up to 5.9m. Time of travel from the dam to the village is about 0.4 hours. Virtually the entire community would be subject to structural damage by fast flowing water. This result confirms the Category A rating of the reservoir.

Under a natural PMF flood the peak flow calculated at Tummel Bridge is 2,298m³/s and the over-bank depth 4.8m, which is close to the currently adopted PMF design flow. The extent of flooding and flood damage is little different from than that for the worst case dambreak.

INITIAL STRUCTURAL ASSESSMENT AND OPTIONS

A technical note on “Strategic Review of Dam Structural Stability and Remedial Options” was prepared in November 2007 [3] based on earlier gravity and finite element stability and stress analyses by Halcrow [8]. The note summarised the findings of a stability review and provided initial consideration of options to address the identified deficit in stability. This concluded that the dam would be stable at the 1:10,000 year flood with an upstream water level of 199.4m aOD, but that both the gravity sections and the gate structure would be grossly unstable under PMF conditions. In the case of the gates, this is because the upstream water level progressively impinges on the base of the fully raised gates.

Engineering remedial options were considered to provide either additional spillway capacity so as to maintain existing water levels under PMF inflows or a stable dam structure under PMF overtopping. To accommodate the PMF within existing water levels would essentially require the dam to be re-constructed, with all the cost, disruption and loss of revenue that this would entail. It would be possible to anchor the gravity section to achieve stability, but not the gate structure. The most promising remedial option for the gate would be to extend the gate piers to lift the gates some 5m higher than is possible at present. However the practicality of such an alteration to a structure already more than 75 years old and showing some signs of deterioration is questionable. Any of these options would be difficult to implement because of the lack of any vehicle access to the dam.

The River Tummel bursts its banks and significant flooding of Tummel Bridge occurs at about the 100 year flood. Much of the village would experience flood damage beyond the 1,000 year event. It is therefore expected that most of the population at risk in Tummel Bridge village would be well aware of extreme flood conditions long before the stability of Dunalastair Dam became critical and seek to evacuate. SSE remotely monitors reservoir levels at Loch Rannoch and Dunalastair Reservoirs, can remotely operate the gates at Rannoch Weir and locally operate the siphon valves and gates at Dunalastair Dam. SSE also informs SEPA, the authority responsible for flood warnings, on changing flow conditions on the River Tummel during high flow conditions. It therefore seems most unlikely that the 1:10,000 year flood and the dambreak threshold could occur without significant prior warning. An option therefore exists to ensure that the occupiers of the limited number of properties at risk in case of a dambreak are evacuated before water levels become critical so that the consequences of a failure of the dam are mitigated.

This strategic approach to improving the safety of the dam has been accepted in principle and background work to confirm and develop this is now in progress.

RISK ASSESSMENT AND MITIGATION

The expected loss of life from a dambreak incident is very dependent on the warning time available, the depth and velocity of flow and the availability of an evacuation plan. Various methods for estimating this are plotted on Figure 9.1 of the QRA guide [9].

At Tummel Bridge the valley is flooded to a width of about 350m. Q/W for the peak of the worst case dambreak is therefore about $10.8m^2/s$. Based on this and the estimated population at risk (PAR) of 350, there are 3 scenarios.

1. With no warning provided, loss of life is estimated at about 40% of PAR, in this case about 140.
2. With a warning of more than 1 hour, but no evacuation plan, the estimated loss of life is about 5% of PAR, in this case about 18.
3. With more than 1 hour warning and an effective evacuation plan carried out under better conditions before extreme flood conditions occur, the estimated loss of life is expected to be near to the 0.1% of PAR suggested as a minimum value, equivalent to a 35% chance of one life lost.

Assuming that dam failure would occur at between the 1:10,000 and 1:50,000 year flood event, the acceptability of the above scenarios can be compared with the limits of risk given in Sheet 11.3 of Appendix C of the QRA Guide [9]. This shows that Scenario 1 is marginally unacceptable; Scenario 2 should be subject to risk reduction where practicable, whereas Scenario 3 is broadly acceptable, and meets the requirement for practicable risk mitigation. This is shown graphically on Figure 2.

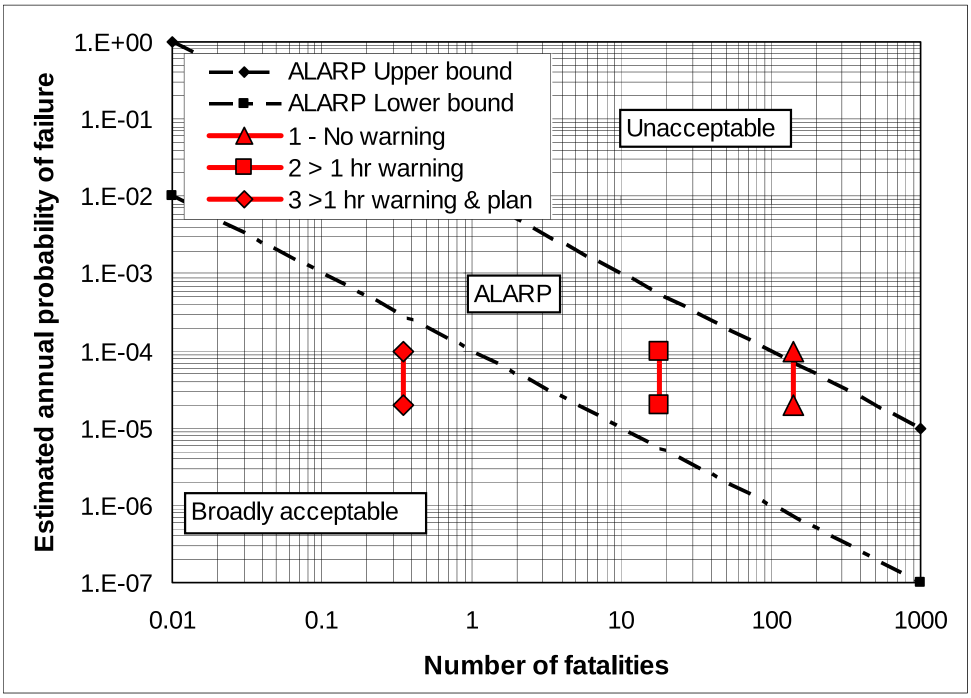

Figure 2. Risk Assessment for Different Response Scenarios

On the same basis, the natural PMF flood would have a Q/W ratio of 9.2m²/s and an estimated Scenario 2 loss of 3.7% of the PAR of about 320, or about 12 persons. Assuming a return period of $1x10^6$ for the PMF, this too is in the broadly acceptable zone of Figure 2.

In the present circumstances, the "no warning" scenario is unrealistically pessimistic for a flood-induced dambreak, because of the flood monitoring and warning role already carried out by SSE, and visible flooding of properties in Tummel Bridge well before dambreak can be expected. However, while some inhabitants of Tummel Bridge would leave their homes as they became flooded, without an evacuation plan in place, others would choose to stay in their homes until evacuation was no longer possible because of the surrounding fast-flowing flood water.

To provide the maximum potential mitigation to loss of life due to both extreme floods and the risk of dam failure under these circumstances, an evacuation plan should be in place to evacuate the population at risk before flood waters make this impossible. The evacuation plan will effectively be an off-site emergency response plan.

In case of Scenario 3 above, in terms of potential loss of life, the presence of a warning and evacuation plan would effectively reduce the flood risk from Category A on Table 1 of "Floods and Reservoir Safety" [Rev 2], as currently assessed, to B. Mitigation of the risks downstream of a dam is not really addressed in any detail in "Dams and Reservoir Safety". It is, however, referred to in passing on page 7 under Category B dams where it suggests escape routes from locations at risk downstream of a dam to reduce the category. This seems to establish a basis for managed evacuation as an acceptable approach to flood risk mitigation.

EMERGENCY RESPONSE (OFF-SITE) PLAN

There are a number of potential difficulties foreseen with implementing an off-site emergency response plan in the conventional way in Tummel Bridge. These include:

- That there are no primary responders (e.g. police) based in the village.
- The village is accessed only by B roads, most of which are liable to be blocked in such an extreme flood, cutting off the village.
- Virtually all the properties in the village are at risk of flooding and there is no obvious site as a place of safety for evacuation.
- Out-of-bank flooding of the village occurs at relatively low return period natural floods, and evacuation under extreme flood conditions would, in itself, be hazardous. Evacuation must therefore take place before the village is extensively flooded.

The preliminary conclusion is that if an evacuation plan for the community needs to be put in place, the organization best placed to develop and carry this out is SSE, with their local facilities and resources. This approach is being adopted for the time being, subject to future discussions with all interested parties. However some initial preparation has been made to better define the risks and flood conditions in Tummel Bridge. These are described in the following sections.

Flood Mapping

The initial dambreak flood assessment used a crude hydraulic model based on widely spaced valley sections and map contours. More detailed assessment of flooding is considered necessary to reliably demonstrate the impacts of both natural floods and dambreak impacts on the Tummel valley downstream of the dam and in Tummel Bridge village in particular. To this end a more detailed 1-d flood model of the Tummel valley between Dunalastair dam and Loch Tummel has recently been prepared, including Tummel Bridge, using LiDAR ground level data. To date flood mapping has been produced for the 1:100, 1:1,000 and 1: 10,000 year natural floods and mapping of the natural PMF is in hand for comparison with the initial "PMF without dambreak" mapping results. It is then intended to carry out further mapping of dambreak floods as necessary.

It is intended to use the more refined dambreak mapping to reliably establish the areas at risk, and possible locations for safe refuge areas. The lower return period flood mapping will be used to predict the flood situation at which evacuation can still be carried out safely. The flood models will also be used to establish the necessary timing for flood warnings.

Dambreak Scenarios

The initial dambreak assessment was based on a worst-case scenario assuming virtually instantaneous failure of the entire dam, although a gate failure scenario was also considered. Further structural assessment of the gravity spillway and gate sections of the dam have been carried out to assess critical modes of failure of the dam.

Gravity section failure

The initial mode of failure of the dam as it currently exists is expected to be failure of the gravity spillway section. This becomes unstable, relying on progressively higher tensile strength at the upstream face lift joints, as water level rises above about 200.0m aOD. However the gravity section is shear-keyed to the adjacent abutment and siphon blocks, and overturning of a limited length of this seems unlikely. It is considered that the most likely way that a failure mechanism could develop is by progressive load transfer to adjacent marginally stable blocks causing failure of the whole gravity section from the left abutment up to and including the north gate pier, which is keyed to the gravity section. The gate piers are only lightly connected to each other by the gate lifting equipment and walkways, and so failure of the north gate pier would not necessarily cause failure of the central pier. It is likely that this failure would take place before the peak PMF water level is reached in the reservoir, and the outflow is rather more restricted than assumed in the previous dambreak study. The peak dambreak flow is therefore likely to be less than that previously assumed.

It would be possible to prevent this mode of failure by anchoring the gravity spillway and siphon sections with rock anchors, although this would require modification of the footbridge above the weir crest.

Gate structure failure
The second mode of failure would take place when the overturning moment from flood water impinging on the gates exceeded the restraining moment provided by the piers. Assuming that the original design of the piers included a factor of safety of at least 1.3 against overturning in the normal flood case, failure would not be expected until upstream water levels rose above 203.1m aOD. The expected failure mechanism in this case is overturning failure of the central pier. This form of failure would not occur unless the gravity sections, which would be expected to fail first, had been anchored. If it did occur, the peak dambreak flow downstream would be significantly less than for failure of the gravity section.

It is intended to use this assessment to consider more realistic dambreak hydrographs for comparison with the PMF without dambreak.

Further work
The approach being developed for Dunalastair Dam is a work in progress, and it is still far from complete. Once the above flood modelling is complete, an updated risk assessment will be prepared to provide justification for the approach currently adopted to provide flood mitigation by preparation of a detailed emergency response off-site plan for Tummel Bridge, which we currently see being managed by SSE.

Once accepted, it will be necessary to:

- Agree a protocol for emergency action with the primary responders and emergency services responsible for the area
- Involve the community
- Develop a practicable evacuation plan, including consideration of facilities and resources required
- Adapt the existing flood warning system to suit the plan

CONCLUSION
It is widely recognized that Emergency Plans mitigate the risks posed by dams, and many of us will shortly become involved in the preparation of on-site, if not off-site emergency response plans. Ulley has shown us all how evacuation of the population at risk can be used to mitigate potential dambreak impacts on a community. However it is still unclear how dam practitioners should apply this in relation to risk assessment methodology and dam standards.

Dunalastair Dam provides a case study where a dam owner has found proactive preparation of emergency plans for the downstream community a pragmatic solution to effectively improve dam safety and mitigate risk where no clearly beneficial or effective engineering solution was available. We need to consider such cases carefully, and agree standards and methods for adopting this type of approach, clearly beneficial to both owner and community, into accepted practice.

REFERENCES.

[1] *Dunalastair Reservoir. Report under Section 10(1).* A. Macdonald. December 2003.
[2] *Floods & Reservoir Safety. 3rd Edition.* Institution of Civil Engineers. 1996.
[3] *Dunalastair Dam. Strategic Review of Dam Structural Stability and Remedial Options.* A C Morison. November 2007.
[4] *Flood Studies Report Volumes I – V.* Natural Environment Research Council, London. 1975.
[5] *Flood Estimation Handbook Volumes 1 – 4.* Institute of Hydrology, Wallingford. 1999.
[6] *Reservoir Inundation Studies. Tummel Scheme. Dunalastair Reservoir (507) – Dunalastair Dam. Final Report.* Babtie Group. May 2002.
[7] *Reservoir Inundation Studies. Consequence Assessment: Dunalastair Reservoir (507) – Dunalastair Dam.* Babtie Group. March 2003.
[8] *Gravity Dam Detailed Stability Review. PMF Assessment of Gravity Dams.* Halcrow Group. February 2004.
[9] *Interim Guide to Quantitative Risk Assessment for UK Reservoirs*. A J Brown & J D Gosden. DEFRA. 2004.