Tackling the Thorny Issue of Spillway Capacity in Yorkshire

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SYNOPSIS. This paper will illustrate by example a number of cases where the problem of insufficient spillway capacity has been dealt with in ways other than just increasing the size of spillway channels. It will also illustrate the benefits of physical modelling and a number of problems associated with the environment and planning restrictions.

INTRODUCTION

Yorkshire Water (YW) has a reservoir portfolio comprising 138 reservoirs under the ambit of the Reservoirs Act 1975, the majority of which are 'Pennine' earth embankments with a puddle clay core. Following the Boltby incident and the subsequent report – 'Spillway Structural Appraisal', (Arup, 2008) – particular attention was focused on Yorkshire Water's masonry spillway systems.

BLAKELEY IRE

Blakeley Impounding Reservoir (IRE) is located in the Wessenden Valley to the south of Marsden, West Yorkshire; the reservoir is the second of four YW reservoirs constructed across Wessenden Brook with Butterley IRE below and Wessenden Old IRE and Wessenden Head IRE above. The reservoir lies wholly within the Peak District National Park (PDNP).

Blakeley IRE is a Category A as defined by the Floods & Reservoir Safety 3rd edition (ICE 1996). The dam is a typical Pennine earth embankment with a puddle clay core and concrete cut off; it is orientated in an East/West direction with the downstream face to the North. The downstream shoulder has quite an unusual shape; to the left of centre, the upper slope is relatively steep at 1V:2.5H, below this there is a partial berm, and then the slope abruptly relaxes to a shallower slope which continues at a constant gradient of 1V:4.5H down to a masonry retaining wall at the tailbay. To the right of centre, a significant buttress, curved in plan, exists. This is thought to be partly due to material excavated from the wing wall trenches of the nearby Butterley IRE being placed against the downstream slope in this area.

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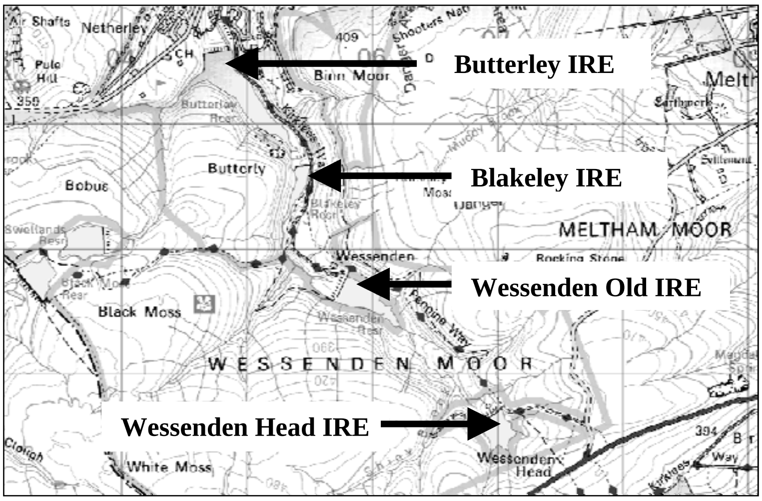

Figure 1. Location plan

Blakeley IRE is fitted with a curved stone 'broad crested' overflow at the western end of the embankment, which discharges into a wide stepped masonry channel down the left mitre. The original construction drawings indicate that the invert comprises 15” (381mm) of dressed ashlar blocks underlain with 18” (457mm) of mass concrete. The invert follows the contours of the downstream slope in a series of small steps with slightly larger steps at 9’ (2743mm) intervals. These larger steps are 3’ (914mm) deep and are keyed into the underlying rock. The spillway walls vary in section, but typical details show a substantial masonry facing which tapers with height and a backing layer of concrete. There are four architectural pillars which protrude some 8” (200mm) into the channel. These pillars are located on either side of the channel at the top and bottom of the steep cascade section.

Beyond the spillway channel is the stilling area which is submerged when Butterley IRE is at top water level; downstream of this is a retaining wall and earth embankments which form the abutment of a light vehicular access bridge.

The reservoir was inspected on the 29th October 2008 by Dr. A. K. Hughes and a report under Section 10(3) of the Reservoirs Act 1975 was issued dated 3rd April 2009. This report contained the following recommendation;

15.2 Recommendations as to Measures to be taken in the Interests of Safety under Section 10(6) of the Act;

(ii) a study of flow depths and velocities and if possible pressures be undertaken and the results discussed with an All Reservoirs Panel Engineer

I recommend these works are undertaken within 18 months of this report i.e. by 3rd October 2010.

In order to satisfy the above recommendation YW commissioned a flood study and physical model of the existing spillway system, the latter being undertaken by CRM Rainwater Drainage Consultancy at Bolton. Dr. A. K. Hughes was appointed as Qualified Civil Engineer (QCE) to oversee and certify the work.

The flood study determined a peak outflow of 176m³/s for the Probable Maximum Flood. A 1/25th scale model was constructed and the hydraulic factors were scaled by Froude number similarity to arrive at a model flow of 56.3l/s. The model was then tested at the following predetermined rates:

1 in 100 year	47m³/s
1 in 500 year	69m³/s
1 in 1000 year (FEH)	84m³/s
Probable Maximum Flood	176m³/s
Probable Maximum Flood +10%	194m³/s

Through the modelling process it was concluded that there were several areas of concern with the existing spillway system that would need to be addressed via physical works. These concerns included: at PMF the still water level was above the watertight element of the dam; the architectural pillars within the channel caused significant plumes of water which impacted on the surrounding ground surface; velocities as high as 20m/s were observed in the lower reaches of the channel; water was impounded by the retaining wall and earth embankments downstream resulting in flows against the toe of the dam. The results of model test at PMF are shown in Figure 2.

If a standard approach were t be taken to address the problems listed a typical solution would result in works to raise the watertight element of the dam; construction of a smooth concrete channel capable of containing the PMF flows and a stilling arrangement to allow flows to pass safely in to Butterley IRE without disruption of the inlet.

It was apparent from the outset that this would be a costly solution which was likely to be subject to significant planning constraints (as has been the case at several other Yorkshire Water reservoirs in the PDNP which have required remedial works) and for this reason an ‘optioneering’ session was held at CRM, Bolton. Several options were explored and ruled out, mainly on effectiveness, ease of construction, visual appearance and cost. Therefore the emphasis was focused on what could be carried out to the existing structure.

The peak still-water flood rise was found to be above the top of the clay core and marginally above the crest level in places. As this could be addressed by raising the clay core and crest it was therefore included in the list of required works.

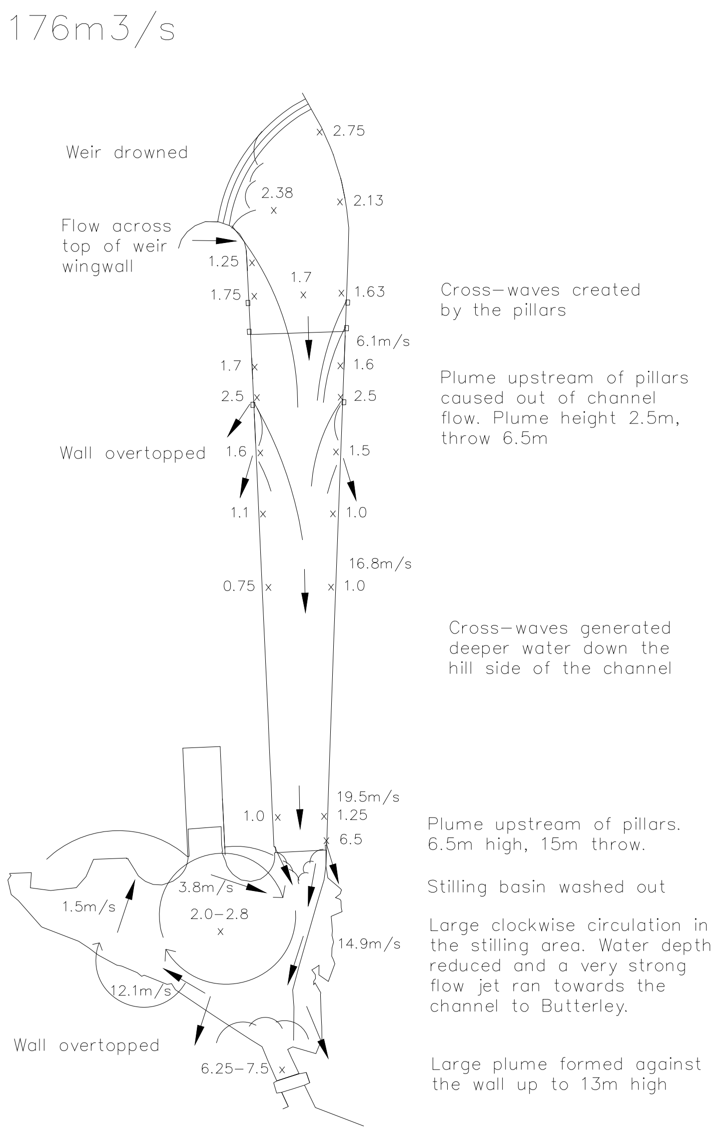

Figure 2. Model test results at PMF – existing situation

The effect of the architectural pillars was unfavourable and it was agreed that these should be modified such that they did not protrude into the channel. These effects can be seen in Figure 3.

The problems now lay with the velocities within the masonry channel and the effect of the earthworks beyond the stilling area. The scenario of the consequences of channel damage/failure during a storm event was discussed. As evidenced from incidents at Boltby and Ulley flood waters could quickly start eroding the earth fill backing to the spillway walls which, if allowed to continue unhindered, could result in catastrophic failure of the reservoir embankment.

Figure 3. Effect of the architectural pillars

As Blakeley spillway was in close proximity to the left hand side mitre and downstream slope it was initially determined that loss of the spillway walls would be unacceptable. Analysis of failure modes suggested that erosion of the embankment was highly likely, although it was thought that if a way of preserving the structural integrity of the embankment could be found, the loss of the walls could be tolerated for such an extreme event. At this point a return to the first principle of embankment protection was considered and the significance of the structural and geological elements of the existing spillway channel structure reviewed. Site investigation had shown that the spillway channel was founded on rock and would not erode under PMF conditions if the overlying channel was washed out. The left hand side channel wall was cut into rock and would remain stable under PMF conditions. The weak section of the channel was the right hand side wall.

Therefore an initial concept of constructing a structural cut-off behind the existing right hand side spillway wall was conceived. The philosophy would be that the new wall would be keyed into competent material to ensure that even if the entire spillway system was lost, the extent of any erosion would be arrested by the presence of the newly created wall.

Finally the issue of water circulating against the toe of the dam would be addressed by the removal of the earth fill embankments downstream of the stilling area to allow clear passage for the flood flow.

To enable the cut-off wall option to work it was important to carry out ground investigations to determine the nature and suitability of the underlying material to allow its construction. The left abutment rises steeply and rock outcrops can be seen dipping towards the axis of the dam, as is shown in Figure 4.

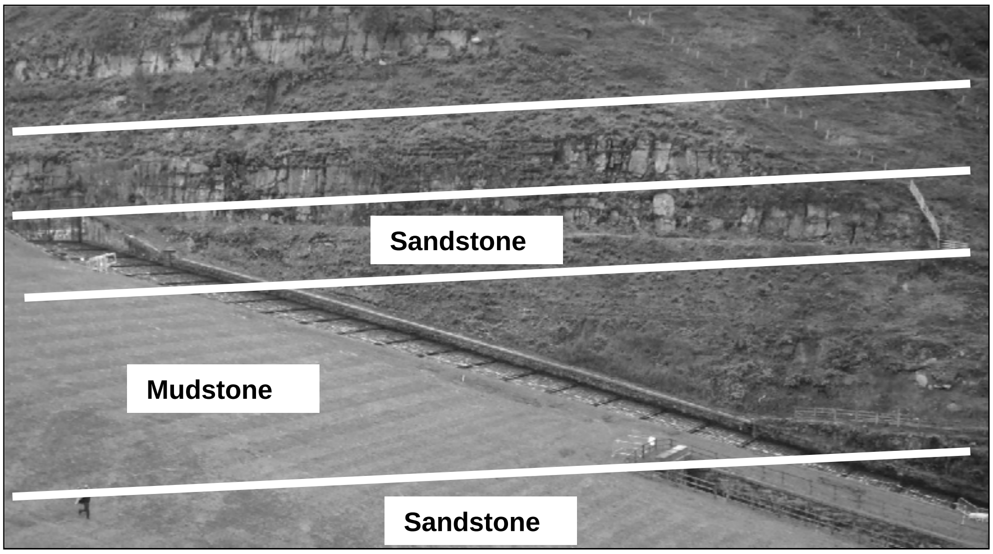

Figure 4. Left hand side abutment showing outcropping rock head

A series of investigative boreholes were drilled through the spillway invert and behind the right hand side spillway wall. The spillway invert was confirmed to be as the original construction drawings; the masonry was backed with concrete and founded on bedrock. The rock head profile behind the right hand side wall was confirmed - in the lower reaches it was found to be sandstone which was rising as a series of large steps in an upstream direction. As the depth of embankment fill increased the rock encountered changed to a mudstone, bedded consistently with the sandstone. A machine excavated trial hole was opened down to the mudstone to gather a better understanding of its engineering properties.

During the design process various methods of construction for the cut-off wall had been considered ranging from in situ concrete to pre-cast concrete (PCC) units. It was finally agreed that the lower section would be constructed from in situ concrete anchored into the underlying sandstone and that this would be connected to a contiguous reinforced concrete piled wall which would be utilised where the mudstone dictated.

The cut-off wall was designed to prevent erosion of the embankment assuming that the spillway system was lost during an extreme flood and therefore it assumes that the rock beneath the spillway would be not be eroded and that the cut-off wall would act as a cantilever and actively retain the embankment.

The contiguous piled wall had added benefits: the speed of construction was increased; no excavation or formwork had to be utilised and there was less visual impact both during and following construction.

Additionally the adoption of the cut-off wall allowed the visual appearance of the spillway channel to remain virtually unaffected. The only exception was the need to remove the architectural pillars, which was achieved by employing stone masons to dress back the masonry face to ensure a solution sympathetic to the existing structure.

The deficiency of freeboard at the crest was investigated along with trial excavations to confirm the top of clay level and construction of the wave wall. The clay level was deficient in places and it was decided to raise it to the required level using puddled clay. It was determined that the wave wall was of sufficiently robust design to resist wave action and minor impounding at the base for the duration of the flood rise.

A further change that was made during the design and construction stage was to revisit the model test with focus on the area downstream of the spillway system. The earthworks beyond the stilling area which form the abutments for a pedestrian bridge had originally been identified for removal to allow passage of flood waters into Butterley IRE, thereby stopping water circulating against the toe and lower areas of the embankment. The model test report confirmed that the velocities of flow in this area were relatively low and it was decided that protection of the toe may be a more favourable solution. The design was revised and it detailed the areas of inundation at the toe of the dam which should be covered in a protective layer of open stone asphalt (OSA). This OSA was covered with topsoil and seeded and hence the outward visual appearance of the embankment remained unchanged. This solution also allowed for the pedestrian bridge to be retained and although this bridge is not required operationally, it does convey a permissive footpath which would have required diversion.

The out turned scheme cost was £0.9 million and allowed a capital efficiency claim of £1.3 million to be submitted against the original proposed concrete spillway reconstruction forecast.

INGBIRCHWORTH IRE

Ingbirchworth IRE was thought to have been constructed by 1868 under the direction of J. H. Taylor, Waterworks Engineer of Barnsley, and is located in near the market town of Penistone in South Yorkshire.

The dam is formed by an earth embankment with a central puddle clay core. The upstream face is protected by stone pitching; the crest carries a tarmac public road; there is a masonry wave wall on the upstream side of the crest and the downstream side has a hedge and fence; the downstream face is grassed with a single berm at approximately mid height.

Overflow from the reservoir is catered for by a broad crested weir, curved in plan, at the north end of the dam embankment. Water flowing over the weir is discharged through a three-arch bridge carrying the public road over the dam crest and then flows down a stone lined stepped spillway channel which discharges into the stream significantly downstream of the toe of the dam embankment. There is no stilling basin.

No original drawings showing the construction details of the spillway channel are thought to exist.

The reservoir was inspected on the 28th July 2005 by Dr. A. K. Hughes and a report under Section 10(3) of the Reservoirs Act 1975 was issued dated 8th January 2006. This report contained the following recommendation;

15.2 Recommendations as to Measures to be taken in the Interests of Safety under Section 10(6) of the Act;

(ii) a physical model be built to understand how the spillway will operate in extreme floods

This recommendation was addressed by commissioning an updated flood study, topographical survey and subsequent physical model. The flood study calculated that the PMF peak outflow would be 57m³/s and given that the model was constructed at 1/25th scale a model flow of 18.2 l/s was derived. The model was tested in stepped increments up to and including a maximum flow of 80m³/s.

The key areas of concern identified by the physical model report were:

- The weir was in free flow up to 43m³/s after which the bridge arches became the restricting factor.
- The drowned weir was capable of passing the PMF with the resultant flood rise below the watertight element of the dam.
- Out of channel flow was witnessed on the right hand side when flows reached 40m³/s; by 57m³/s the depth of flow was 1.175m and extended to a width of 2m on the adjacent hillside.
- Maximum velocities of 13.1m/s and 8.6m/s respectively were observed in the channel and on the hillside.
- The flow ran supercritical from the end of the spillway channel and did not turn to follow the original stream path.

It was accepted that as the spillway system was remote from the reservoir embankment and the topography was such that there was an expanse of original ground between the channel and the left hand side mitre that the scope of work required may be minor in nature. Trial holes were requested to ascertain the spillway construction given the uncertainty surrounding its construction.

The trial holes indicated that the masonry spillway walls were backed with concrete and that they would be sufficiently robust to withstand the flood flows provided they were adequately maintained. The invert of the spillway had been overlain in 1995 with a protective layer of un-reinforced concrete where the original masonry had deteriorated.

The model report and findings from the physical investigations led the QCE to make the following recommendation as to measures to be taken in the Interests of Safety under Section 10 of the Act Follow on Work;

I recommend the spillway is repaired under the direction of a QCE in all areas where the velocities are greater than 9m/s paying particular attention to the ends of the slabs and areas which are known to be deteriorating.

A delivery contract was issued to Yorkshire Water's term contractor Mott McDonald Bentley (MMB) to address this recommendation and a site walkover was carried out with the QCE to identify the areas which would require attention. It became apparent during this walkover that the slabs had deteriorated further since the original Section 10 inspection and that simple repairs may no longer be sufficient. The QCE therefore advised that the concrete should be removed from the invert and be replaced with a reinforced concrete slab. The area of new concrete was again to be concentrated where it would be subject to the higher velocities. It was still thought that re-pointing of the walls would be effective to ensure their longevity and integrity.

The work on site was started in April 2011 and the early stages involved the removal of the defective concrete invert and raking out of the mortared joints to allow re-pointing. During this process it became evident that there were several sections of wall which were of poorer construction, and further investigation, involving the removal of the copings, highlighted that the masonry skin to the walls was not backed with concrete as earlier investigations had suggested. The original wall construction is shown in Figure 5.

Figure 5. Showing the original wall construction

The information was passed to the QCE and the core team involved with the project and initial discussions were had regarding alternative solutions. A full section of the spillway wall was removed and the construction of the wall was examined – this was confirmed as a masonry facing course, backed with rubble bound in mortar, with a further backing layer of puddled clay to the batter of the original excavation. The spillway invert was known to be masonry underlain with concrete which was founded directly on the excavated left hand abutment.

Yorkshire Water and the QCE were now faced with a new problem which the original solution would not address; the scope had changed from refurbishment of the existing structure to a potential rebuild of the entire lower section of channel.

Yorkshire Water's asset standards dictate that spillway systems need to be designed to water retaining codes and this would lead to an expensive solution. With this in mind, discussions were held to consider what alternatives were available. Attention returned to the topography of the site and the model test results, which led to the proposal to rebuild the spillway channel to a lesser engineering standard due to its remoteness from the embankment.

The original design was modified thus: the reinforced concrete invert slab was connected via dowels to the footing of the spillway wall; the walls were taken down and the masonry face was rebuilt; the backing rubble and puddle clay was replaced with mass concrete and the wall copings were replaced. The design also now incorporated raising of the left hand side wall where the model test indicated out of channel flow. This raising was achieved using local stone sourced to match the existing.

The relaxation of Yorkshire Water's asset standards led to a final scheme cost of £0.95 million against the original forecast of £1.4 million.

Figure 6. The completed spillway at Ingbirchworth

Additional work was carried out on site to address the deficiency in freeboard to the top of the watertight element, utilising a mass concrete cut-off wall keyed into the existing puddle clay core.

The completed scheme allowed for a channel that was visually unchanged (Figure 6) and was granted permitted development by Barnsley Metropolitan Borough Council's planning department.

BUTTERLEY IRE

As mentioned above Butterley IRE is located at the foot of the Wessenden Valley and has a further three Yorkshire Water reservoirs upstream along with two more owned and operated by British Waterways.

The dam is a typical Pennine earth fill embankment, with a puddle clay core and concrete cut-off. The upstream slope of the embankment has a slope of 1V:3H, and is protected by heavy masonry pitching over the upper slope. Below and on the left hand side is rip-rap, which is continued upstream along the left hand side of the valley. On the right hand side the upper part of the slope is heavily pitched down to the flat area in front of the overflow which is covered in more rip-rap. The grassed crest is 6m wide and has a masonry wave wall. The downstream face has a slope of 1V:2.5H with four berms, all of which have vertical rubble drains at the upstream edge.

Butterley IRE is fitted with a curved stone ogee profile weir at the eastern end of the embankment which discharges into a stepped masonry lined spillway channel and thence to a stream. The spillway system shares a number of aesthetic features with that of Blakeley IRE, including the architectural pillars. One significant difference from Butterley IRE is the presence of two steep stepped cascade sections towards the bottom of the spillway channel.

A footbridge crosses the spillway and forms part of the route of the Trans-Pennine bridle path as well as the boundary to the PDNP. A search of the British Listed Buildings website revealed that the stepped masonry channel and the outlet tunnel portal are both Grade II listed structures.

The reservoir was inspected on the 29th October 2008 by Dr. A. K. Hughes and a report under Section 10(3) of the Reservoirs Act 1975 was issued dated 3rd April 2009. This report contained the following recommendation;

15.2 Recommendations as to Measures to be taken in the Interests of Safety under Section 10(6) of the Act;

(i) a study of flow depths and velocities and if possible pressures in the overflow be undertaken and the results discussed with an All Reservoirs Panel Engineer - I recommend this work be carried out within 12 months of this inspection i.e. by 29th October 2009.

(ii) an investigation be undertaken into the integrity of the overflow channel under the direction of an All Reservoirs Panel Engineer who would then direct repairs either permanent or temporary in the light of the results or pending results of the research currently underway into

the performance of masonry spillways. I recommend this work is carried out within 18 months of the date of this inspection i.e. 29th May 2010.

A flood study was carried out and as the reservoir is the bottom of a cascade of six reservoirs a relatively large PMF peak outflow of 241m³/s was derived.

CRM at Bolton again constructed a scaled physical model of the spillway system; the limits of this model were extended to include the confluence with the tunnel outlet channel and the arched masonry bridge further downstream. The physical model was constructed at 1/30th scale due to the magnitude of the design flow and the extent of the downstream topography and was tested at a predetermined flows ranging from 13.7m³/s through to 265m³/s (PMF +10%).

The results of the test were included in a model report issued by CRM and the salient areas of concern were;

- Significant out of channel flow on the right hand hillside.
- Plumes of high velocity water caused by the architectural pillars.
- Separation of the flow from the masonry invert at the cascade sections.
- Significant out of channel flow on the left hand side impacting on the tunnel outlet channel.
- Velocities reached a maximum of 17.2m/s.

The model test results and the discovery that the spillway was a listed structure led the QCE to make the following recommendation as to measures to be taken in the Interests of Safety under Section 10 of the Act:

My initial thoughts are that I consider that the following works need to be carried out:

- *The major 'steps' near the base of the spillway need to be removed by smoothing out the profile between the channel upstream and downstream of the steps. The new base can be formed as a stepped channel as per the rest of the channel.*

- *The base of the channel needs to be replaced as a reinforced concrete base either as a smooth base or as a stepped channel as per the existing*

- *The walls need to be made higher from reinforced concrete. A masonry facing to the floor or walls could be removed in the high velocity flows likely to be experienced which could cause damage or blockage.*

- *The pillars need to be cut back flush with the walls.*

The results of the model test are illustrated below in Figures 7 and 8.

Figure 7. Model test results at PMF – effects of the architectural pillars

Yorkshire Water has started consultation with the local planners, councillors and general public; the key focus of the interested parties is the conservation of the existing spillway in its current condition. The model test has served to highlight deficiencies with the channel and there is no scope to retain the spillway channel in its original as-built design as a primary overflow system.

The option of carrying out similar work to the Blakeley scheme has been considered; however the underlying ground conditions, known problems with the channel and site access arrangements all prohibit this option.

The planning process is ongoing and due to the listed status of the structure may lead to a delay to the physical works. Yorkshire Water's investigations under the MIoS recommendation show that the existing spillway system requires remedial work and the proposal is to address the engineering concerns and to provide a solution sympathetic to the existing structure. This may include:

- The masonry invert to be replaced with a structural concrete slab; this would replicate the series of small steps currently present.
- The walls to be replaced and heightened using reinforced concrete with a form lined finish.
- The existing masonry copings to be retained.
- The architectural pillars to be replicated in concrete; however they will be set flush with the channel walls.
- The steep stepped cascade section to be levelled through, such that the spillway will have a constant grade from top to bottom.

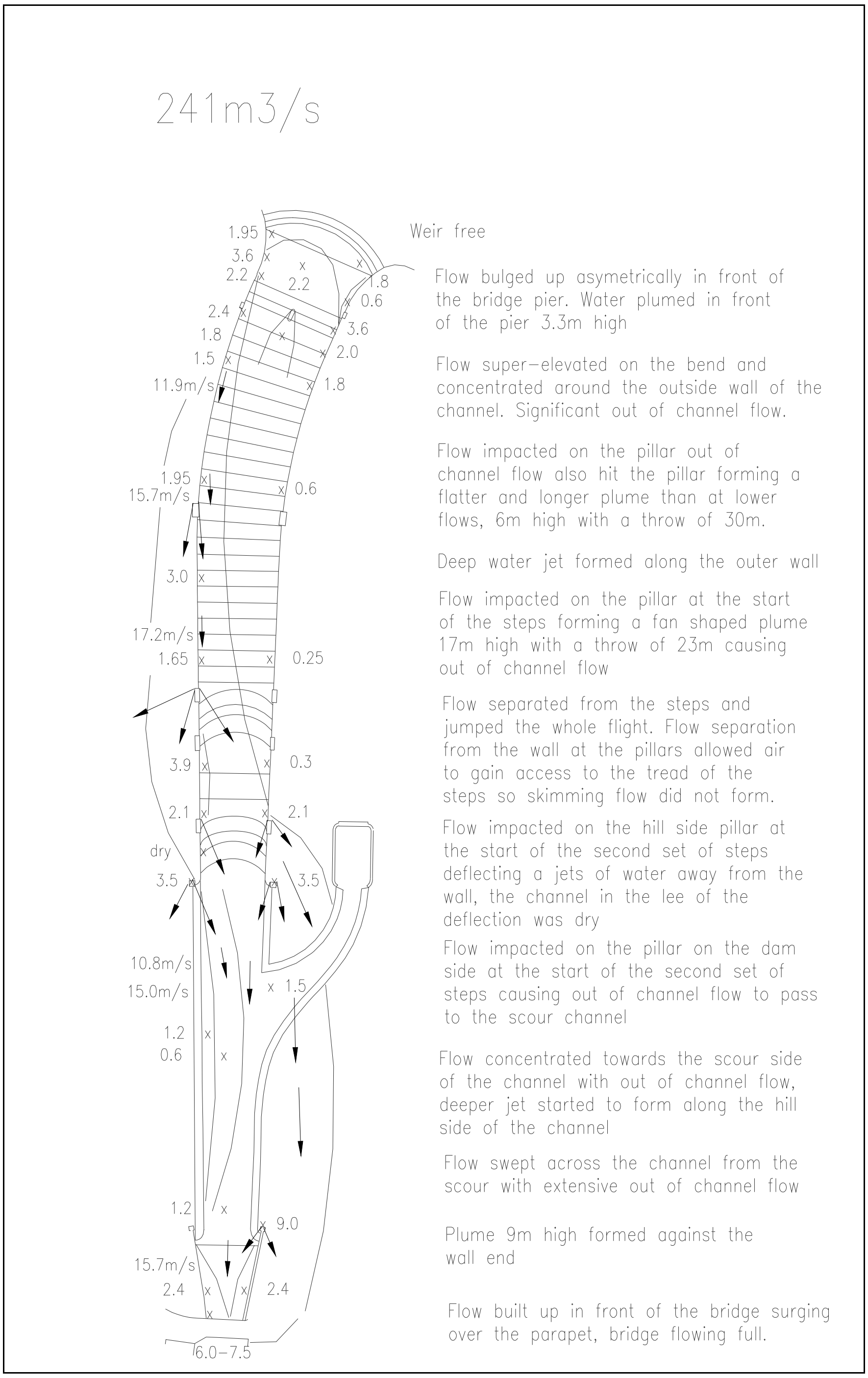

Figure 8. Model test results at PMF – existing situation

PHYSICAL MODELLING

Yorkshire Water is a strong advocate of physical modelling and believes there are distinct benefits in their use. The models are relatively inexpensive to commission and give a high level of certainty, particularly for spillways with complex alignments and topography.

The models have progressed from clear Perspex channels and it is now possible to include the surrounding terrain and therefore probable routing in the case of out of channel flow; where cross waves form and where flows leave and rejoin the channel. The option is available to test at different flow conditions which can be related back to storm return periods.

The model also forms the starting point for the generation of a notional solution, in Yorkshire Water's experience it is unusual that a commissioned model has been tested and no hydraulic problems have been identified. The models are constructed in a manner to allow modifications which will convey the design flood and these can be performed quickly (in some cases whilst you wait). The models are then run to a maximum flow of PMF +10% to provide sensitivity checking.

Additional benefits are the ability to investigate theoretical scenarios, an example being Ingbirchworth IRE, where the crest road is carried over the spillway by a three-arch bridge. It was possible to observe and record the effects of blockages to these archways, ranging from one blocked arch to all three being blocked. The bridge could also be removed with ease to allow this condition to be tested.

The models have also been used to investigate historical impacts upon the spillway. In July 2002 a flood occurred which resulted in a strong overflow of water at Butterley IRE; anecdotal records indicate that the overflow was in the order of 300mm head over the spill weir. Significant damage occurred to the lower spillway system, with masonry blocks being plucked from the invert of the channel (Figure 9).

Figure 9. Spillway damage at Butterley IRE

Whilst modelling the spillway system at Butterley it was decided to run the model at a flow representative of the 2002 flood flow – this was a relatively modest 13.7m^3/s. It could be observed that even at this low flow, velocities reached 7.7m/s and strong plumes of water were generated by the architectural pillars. The area of masonry plucked from the invert was where the plume impacted and it was concluded that this was a contributing factor to the failure of the masonry steps

CONCLUSION

Model testing of these three Yorkshire Water spillway systems has proved to be of great benefit and has generated a robust notional solution in each case. The solutions have been innovative in nature and have, through the use of the models, allowed for work other than traditional u-shaped concrete channels.

It has been possible at Blakeley and Ingbirchworth IREs to engineer solutions that have ensured the integrity of the embankment whilst remaining visually unchanged and although this has not been possible at Butterley IRE a solution has formulated which is as sympathetic to the original structure as current engineering practices allow.

The innovative solutions at Blakeley and Ingbirchworth IREs have led to significant cost savings, reduced planning issues and a significantly reduced delivery period.

The physical works at Butterley IRE are due to commence in the summer of 2012 subject to planning constraints.

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