Guidelines from hydraulic model tests on stepped masonry spillways

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SYNOPSIS As part of an Environment Agency funded project to produce new guidelines for stepped masonry spillways, laboratory tests were performed to investigate the pressure distribution on the spillway walls at the steps and to determine factors that would influence the failure of an individual masonry block.

Zones of high and low pressure were noted on the walls; on a real spillway these zones will typically be only a metre or so apart. If poor pointing allowed the positive pressure to be transferred to the back of the wall it is not inconceivable that it could push outwards on a block that is receiving suction pressures on the front face. On a typical UK spillway the difference between the peak positive pressure fluctuation at the back of the wall and the peak negative fluctuation on the front face could be in excess of 6m water pressure.

Pressure measurements around an instrumented block showed that the worst case was the loss of vertical pointing upstream of a block that stood slightly proud of its neighbours or downstream of a block that was indented compared to its neighbours. The data show that for a typical UK application, a block standing as little as 20mm out of line would be vulnerable to failure.

INTRODUCTION

Following the failure of a number of masonry spillways, notably Boltby (Walker, 2008) and Ulley (Hinks and Mason, 2008), the Environment Agency commissioned MWH to investigate the stability of masonry lined spillways and produce new guidance. As part of that work, CRM Rainwater Drainage Consultancy constructed a high velocity test facility that was used to investigate the pressure distribution on the walls of a stepped spillway

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and to determine the factors influencing the failure of an individual block. The outcome of this research and associated design guidance is presented in this paper. Winter (2010), discusses further aspects of the project and associated guidance.

TEST FACILITY

A 300mm wide chute with a gradient of 1 in 3 and slope length of 7.32m was constructed down the outside of CRM's laboratory at Farnworth, Bolton, Figure 1. Water was fed to a stilling tank on the roof of the building at flow rates up to 70 l/s by the laboratory pump recirculation system and allowed to accelerate by gravity down the chute. For some tests the chute was left smooth, in others it was roughened with strips of timber.

Figure 1. Test Facility

For the first set of tests the bottom half of the chute was gradually narrowed from 300mm to 170mm with a long taper and a flight of Perspex 170mm wide steps were mounted on the end of the acceleration chute. Pressure tappings were placed in the walls and channel invert. Figure 2 shows the effective configuration when applied to a single step. The pressure was transferred through the channel walls in 2mm outside diameter copper tube to a SensorTechnics temperature compensated pressure transducer. The transducers were sampled simultaneously in real time using an Amplicon PCI260i high speed analogue/digital converter data collection card in a Windows PC. The normal sampling rate was 500 Hz per channel.

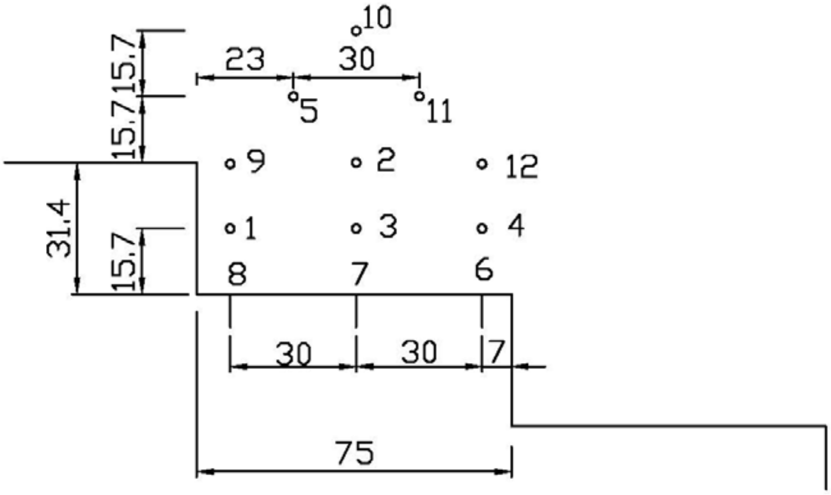

Figure 2. Pressure tapping arrangement for the stepped channel tests (dimensions in mm)

In the second phase of testing, the chute was modified so that it had a width of 60mm along its entire length. At the bottom of the chute the channel was projected horizontally and a test 'masonry' panel was installed in the wall. This panel consisted of a timber sheet with grooves cut to simulate mortar joints between blocks and a 100mm x 50mm movable block in the centre of the panel, Figures 3 and 4. Pressure tappings were provided on the face of the movable block and in the upstream and downstream joints.

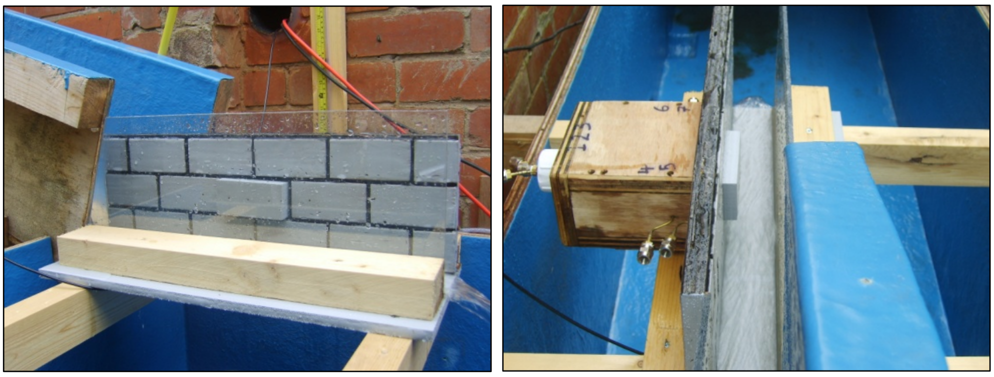

Figure 3. Movable test block

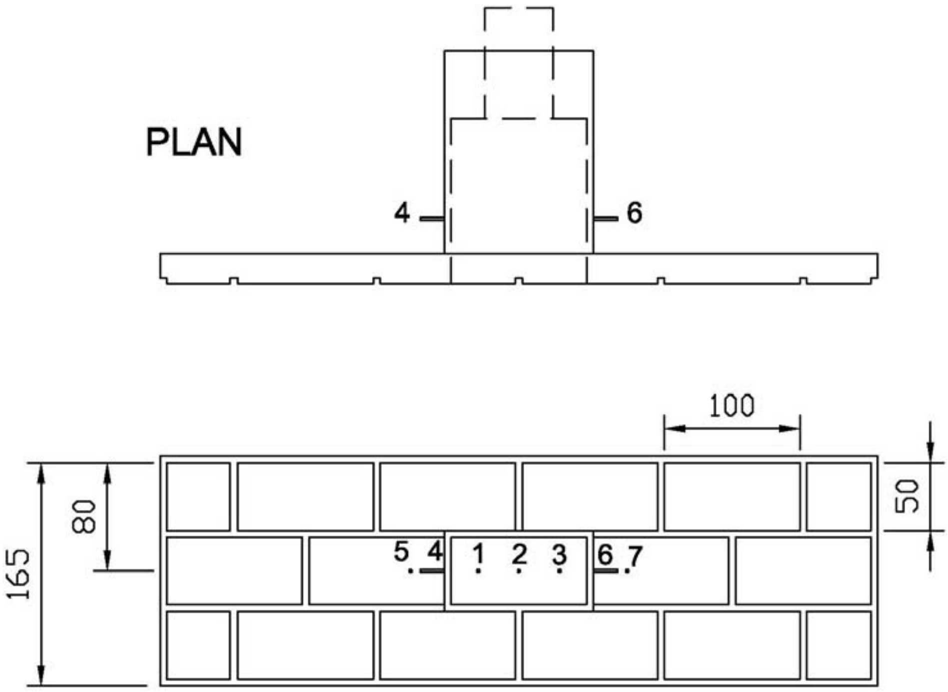

Figure 4. Pressure tapping arrangement for the movable block tests

PRESSURE DISTRIBUTION ON THE WALLS

Whilst stepped spillway surfaces have been investigated in the past, Minor and Hager (2000) and Chanson (2002), the emphasis has been to examine pressure distribution on the face and tread of the steps rather than on the walls at the side of the channel. As skimming flow passes over the edge of a step, the flow separates from the spillway surface and re-attaches part way along the next step downstream. A low pressure roller forms in the lee of the step which generates a zone of low pressure on the wall of the channel. At the re-attachment point, a zone of high pressure is generated. The turbulent pressure fluctuations in these zones will generate peak pressures that are significantly higher and lower than the mean pressure value. Failure will thus be a probabilistic event occurring at random when the forces coincide in an unfavourable manner. A static analysis based upon mean pressure and forces will dramatically under-estimate the risk of failure.

Figure 5 shows the mean pressure distribution on the walls of the model test facility whilst Figure 6 shows the change in pressure distribution caused by having an end sill on the step, an arrangement that is sometime used to promote the formation of a hydraulic jump when the spillway is operating in a nappe flow regime.

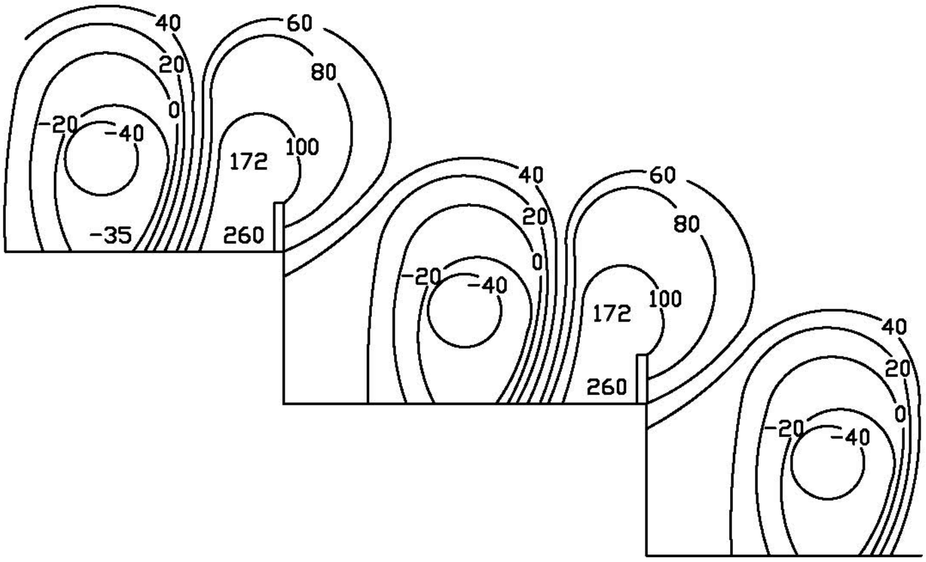

Figure 5. Model average pressure contours (mm water)

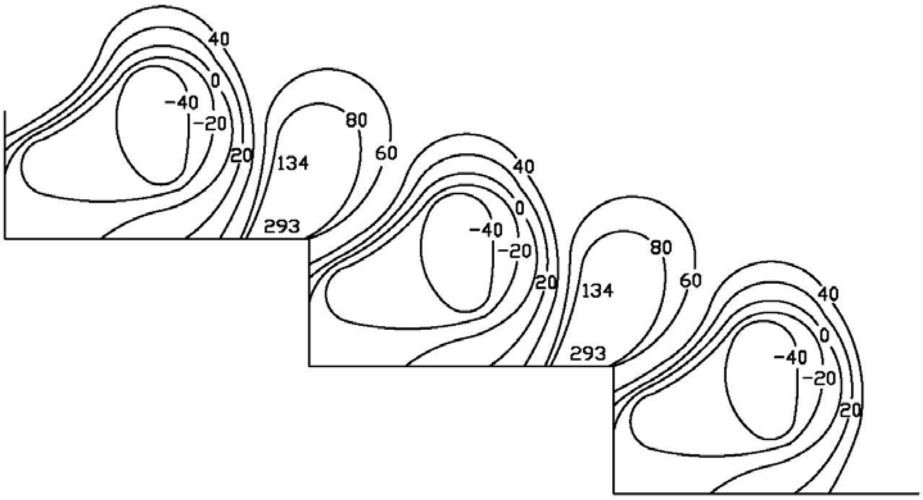

Figure 6. Model average pressure contours (mm water) with an end sill

On a real spillway the zones of high and low pressure will typically be only a metre or so apart. If poor pointing in the high pressure zone allows the positive pressure to be transferred to the back of the wall it is not inconceivable that it could track to the back of the wall in the low pressure zone and push outwards on a block that is already receiving suction pressures on the front face. Figure 6 shows the growth of peak pressure differential, which is the minimum recorded negative pressure in the low pressure roller compared to the maximum positive pressure at the re-attachment point, with increasing flow rate. The model is around 1:10 scale of a typical UK stepped spillway and thus it would not be unreasonable to expect the difference between the peak fluctuation either side of the block to be in excess of 6m water pressure. It should be noted that invert blocks could also experience this pressure differential across a step. Figure 6 compares the data for the cases with and without the end sill and suggests that at higher flow rates the end sill makes the pressure differential worse.

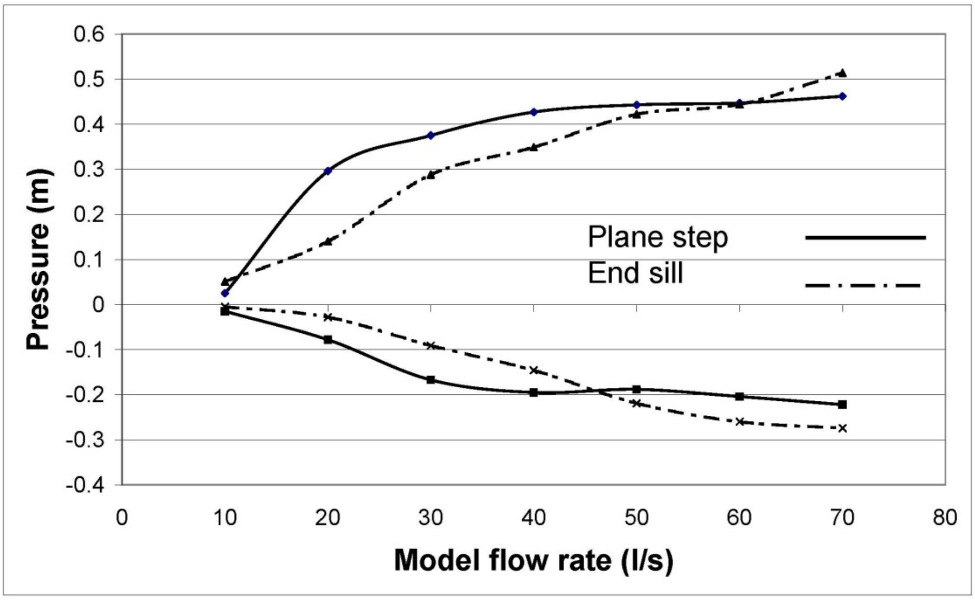

Figure 6. Development of peak pressure differential with flow rate

Failure is far less likely to occur in a well pointed and maintained spillway with no voids at the back of the wall where the pressure fluctuations cannot transfer to and across the back of the wall.

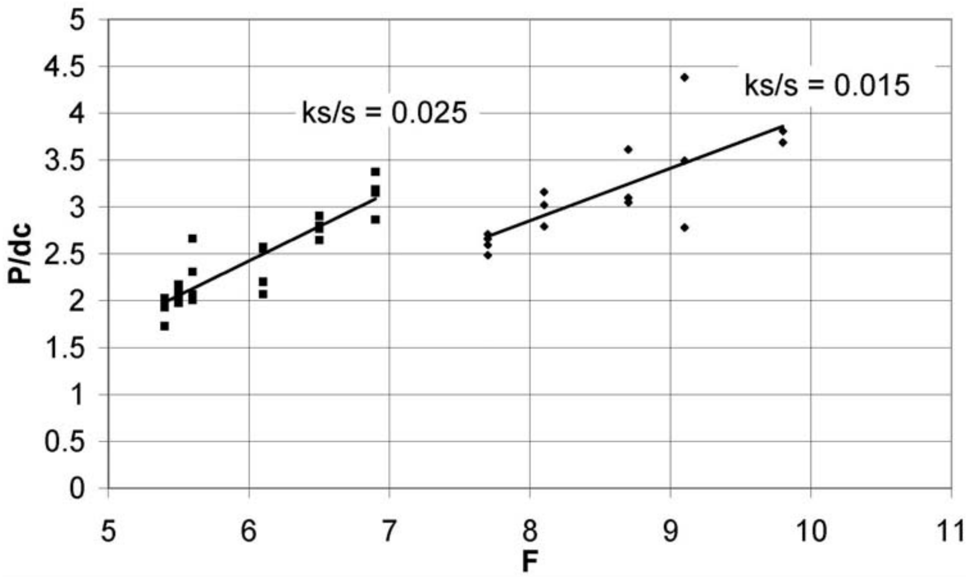

Figure 7. Pressure differential design chart

Figure 7 shows a design chart that could be used to ascertain the likely pressure differential for a stepped spillway, where:

F	is Froude Number
ks	is surface roughness of the spillway surface
s	is step height
P	is maximum pressure differential
dc	is critical depth

BLOCK FAILURE

When a high velocity stream of water was directed past a loose masonry block that stood slightly proud of other blocks in a wall a stagnation pressure developed on the outstand edge. This allowed the velocity head to transfer to the back of the block, instigating failure. Thin blocks and blocks with tapered edges making the back face smaller than the front face failed by rotation about the downstream edge whilst thick parallel sided blocks failed by sliding out of the wall.

Pressure measurements around an instrumented block showed that the worst case was the loss of vertical pointing upstream of a block that stood slightly proud of its neighbours or downstream of a block that was indented compared to its neighbours. Figures 8a and 8b relate the degree of protrusion of the block to the percentage of the depth averaged velocity head that can be mobilised; this shows that for a typical UK application a block standing as little as 20mm out of line with its neighbours is vulnerable to failure.

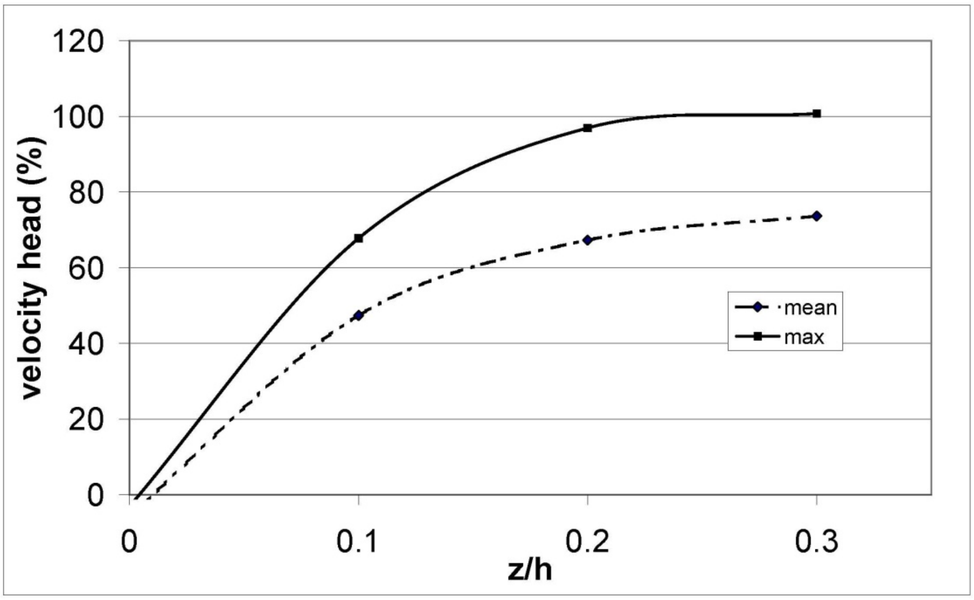

Figure 8a. Percentage of velocity head mobilised by a block that is out of line with its neighbours. Upstream joint with block protruding.

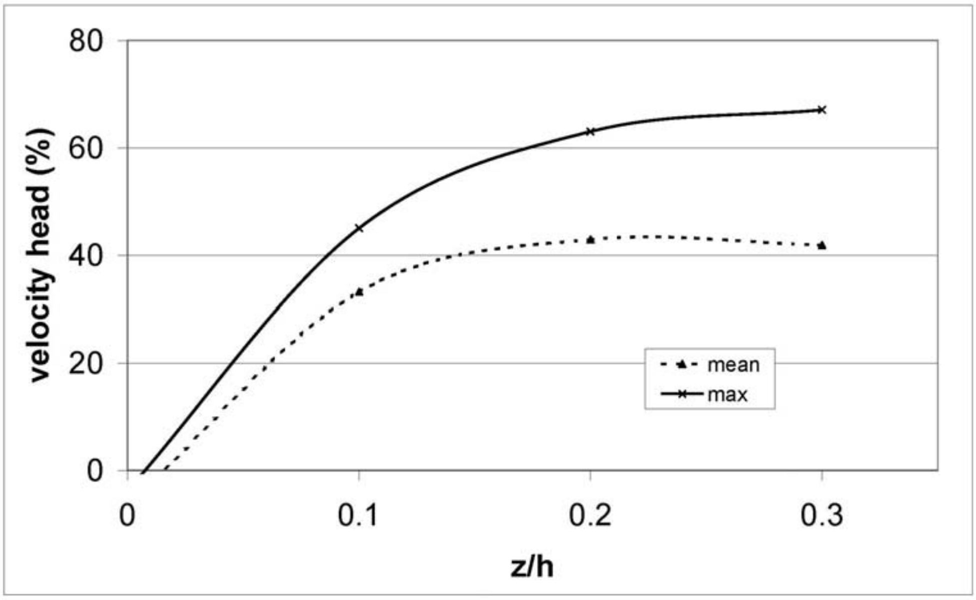

Figure 8. Percentage of velocity head mobilised by a block that is out of line with its neighbours. Downstream joint with block inset.

Where:

z is the amount the block is out of alignment

h is the vertical dimension of the block

Pressure tests on poorly pointed blocks showed that missing pointing from horizontal joints was less critical because it allowed a degree of pressure relief from the stagnation pressure generated at a vertical joint. The tests showed that pointing missing from a few vertical joints is a worse case than poor overall pointing from the viewpoint of the mobilisation of velocity head to generate the failure of an individual block.

CONCLUSIONS

Water flowing over a stepped masonry spillway will form zones of low and high pressure with considerable turbulent fluctuation which on the real spillway may only be a metre or so apart. If poor pointing allowed the positive pressure to be transferred to the back of the wall, it is not inconceivable that it could push outwards on a block that is receiving suction pressures on the front face. On a typical UK spillway, the difference between the peak positive pressure fluctuation at the back of the wall and the peak negative fluctuation on the front face could be in excess of 6m water pressure. Failure will thus be a probabilistic event occurring at random when the forces coincide in an unfavourable manner. A static analysis based upon mean pressure and forces will dramatically under-estimate the risk of failure.

Pressure measurements around an instrumented block showed that the worst case was the loss of vertical pointing upstream of a block that stood slightly proud of its neighbours or downstream of a block that was indented compared to its neighbours. The data show that for a typical UK application, a block standing as little as 20mm out of line is vulnerable to failure. It was observed that pointing missing from a few vertical joints was a worse case than poor overall pointing from the viewpoint of the mobilisation of velocity head to generate the failure of an individual block.

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