Modelling of composite type variation of the Crump weir

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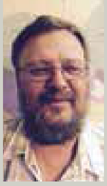

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INTRODUCTION

The accurate measuring of flow in rivers is essential for optimal utilisation of the surface water resources in South Africa. Long-term hydrological records containing the characteristic parameters of change and variability are required for the effective management and conservation of scarce water resources. The runoff from catchments is measured by using gauging structures in rivers and at dams. In South African rivers, the use of compound gauging weirs is common due to the large variation in flows. This allows for accurate measuring of discharge in a river section at low and high flow rates (Wessels & Rooseboom 2009).

Most of the gauging structures built in South Africa are compound Crump weirs consisting of a structure with a series of individual weir crests, each at a different level. The BSI 3680 standards require that compound Crump weir structures be constructed with divider walls. These divider walls ensure that the flow lines over the Crump weir are parallel, minimising errors in measuring the discharge.

Water level readings just upstream of the crest of the Crump weir are used to calculate the discharge over the structure. The flow can be accurately measured for each of the weirs, during submerged and unsubmerged flow conditions, if the water level and the energy line are lower than the divider walls (within the capacity of the structure). Limited studies have been undertaken for discharges over the compound weir structures where the water level is above the divider walls (exceeding the structure capacity). Uncertainties therefore exist applying the developed Crump weir theory for overtopped divider walls.

Extending the application of the Crump weir theory to determine the flow rate during overtopping of the divider walls, results in errors in the rating of the structure during high flow conditions.

The recorded high flows are used to determine flood peaks, for the design of infrastructure such as the sizing of bridges and spillways for dams, for flood line determination for town development, and are also essential to quantify the yield capacity of the surface water resources. This emphasises the importance of accurate flow measurements. Inaccurate measurements could lead to the failure of structures at high flows or result in the overdesigning of structures and incorrectly quantifying the yield growth opportunities, placing a burden on the country's capital resources.

Research directed towards investigating the effects of overtopping of divider walls was identified, allowing for the construction of more cost-effective gauging weirs, and for the early prediction of flood events.

Objectives of the study

The purpose of the study was to determine whether the discharge-head relationship for compound Crump weir structures tested beyond their capacity requires special attention, by investigating the following aspects:

- The influence of overtopping of the divider wall on the water level measured at the observation point.
- The water level above the crest of the Crump weir at which the effects of overtopping of divider walls become negligible.
- The influence of the varying Crump weir width on the effects of overtopping of the divider walls.
- The impact of a varying pool depth on the discharge–height relationship of overtopped divider walls.

Scope of the study

A physical model study was undertaken of a standard Crump weir with a varied crest length. Modular flow conditions were studied, and no influences of submergence were considered.

Three different Crump weir widths with two different pool depths were tested. The divider wall was first set at the standard height to investigate the effects of overtopping. Then a second test was run with the divider wall sufficiently raised to prevent overtopping. The thickness and length of the divider wall were kept constant throughout the study. Each test was run only once.

CRUMP WEIR STRUCTURES

The Crump weir has a triangular profile with the upstream slope as 1:2 and the downstream slope as 1:5. In South Africa it is recommended that the upstream water level gauging point should be double the height of the total design energy head (H_d) from the crest of the weir. The canal walls should be vertical, straight and parallel and should extend at least twice the total design head upstream of the crest of the weir (Wessels & Rooseboom 2009).

The water upstream of the Crump weir normally flows relatively slowly and obeys the fundamental relationship of Q = cross-sectional area x mean velocity. As the water approaches the weir, the cross-sectional area decreases, causing an increase in velocity. The water then flows over the crest, converting its potential energy to kinetic energy. The water level downstream of the weir decreases as the water accelerates under gravity – the flow is then termed 'supercritical'. The supercritical flow, and the 'hydraulic jump' which occurs downstream, cause serious erosion of the river bed. A hydraulic jump is an abrupt rise in water level when flow changes from a supercritical to a subcritical state, with associated dissipation of energy (Beach 1984).

The major advantage of the Crump weir is that the discharge coefficient stays steady and constant during modular flow conditions and the structure is relatively insensitive to non-modular flow conditions (Wessels & Rooseboom 2009). The flow conditions are defined as follows:

Modular flow (not submerged): Occurs when the downstream water level does not influence the water level upstream of the Crump crest (Figure 1). It is therefore possible to determine the flow over the weir by taking a single measurement upstream.

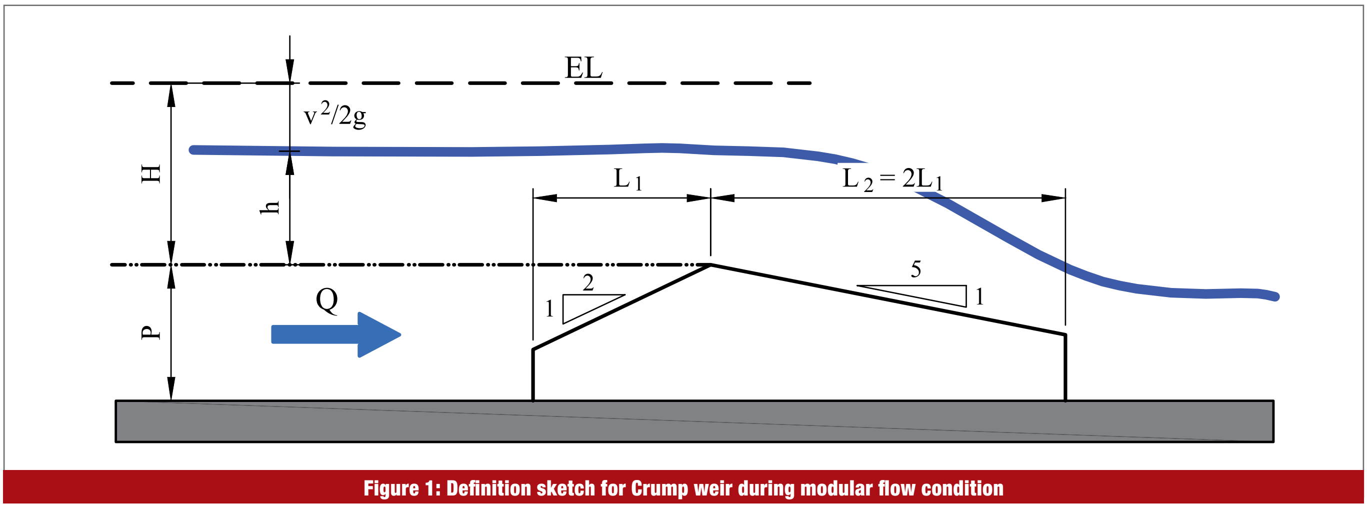

Figure 1: Definition sketch for Crump weir during modular flow condition

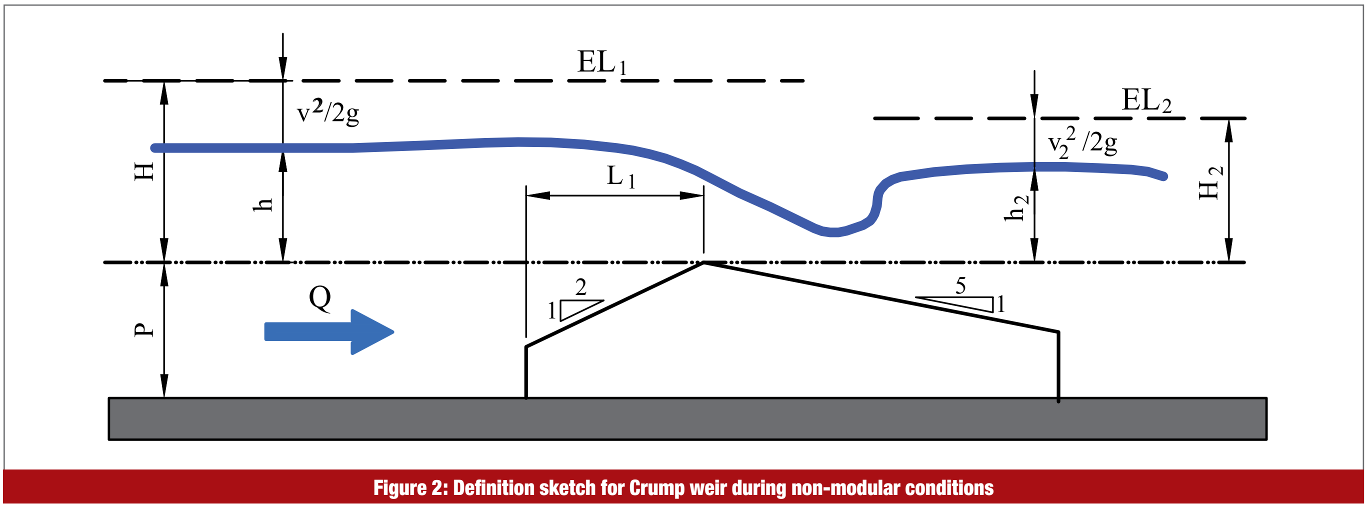

Figure 2: Definition sketch for Crump weir during non-modular conditions

The formulae to determine flow rate over a Crump weir for modular flow conditions (Wessels & Rooseboom 2009) are:

$$Q = \frac{2}{3} C_{de} \sqrt{\frac{2}{3} g}\, b\, H^{3/2} \qquad (1)$$

Where:

$$C_{de} = 1.163 \left(1 - \frac{0.0003}{h} \right)^{3/2} \qquad (2)$$

$$H = h + \frac{v^2}{2_g} \qquad (3)$$

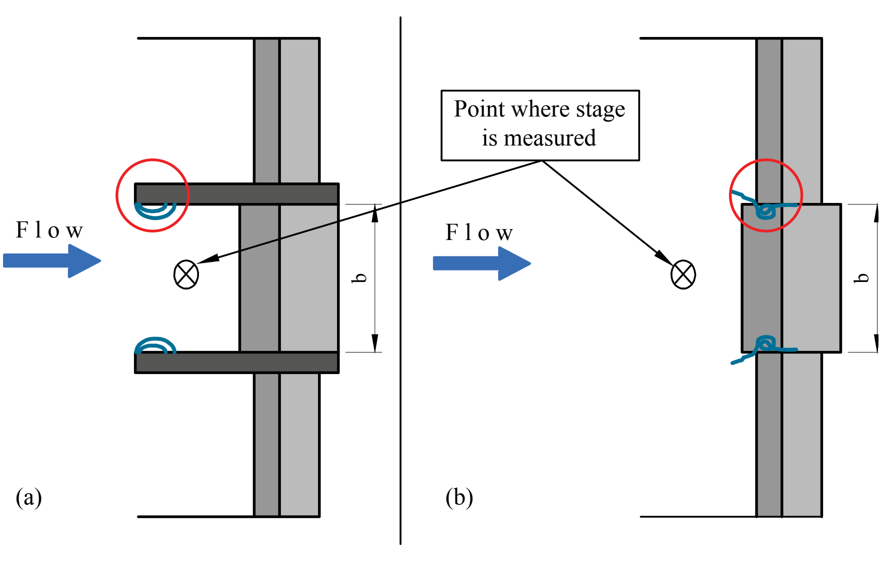

Figure 3: Flow patterns at a compound weir structure: (a) with and (b) without divider walls (Wessels & Rooseboom 2009)

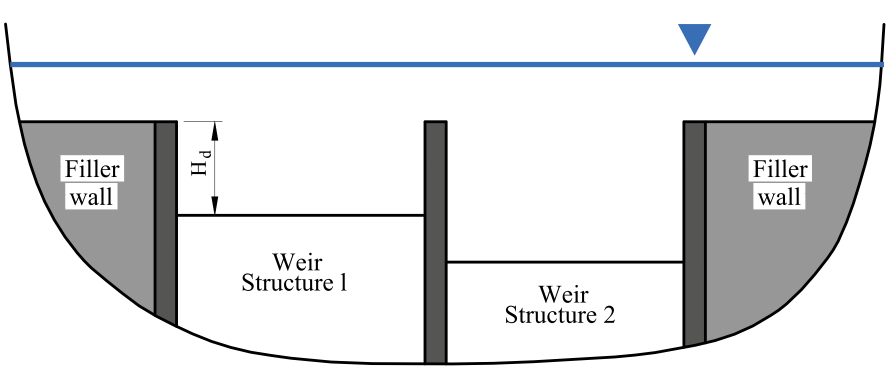

Figure 4: Cross-section of a compound weir with filler walls in a river section

The formulae and definition sketch (Figure 1) parameters are as follows:

C_{de} = Modular coefficient of discharge
b = Breadth of crest perpendicular to the flow (m)
H = Total energy head upstream relative to the weir crest (m)
h = Measured water level upstream relative to the weir crest (m)
v = Mean velocity upstream from the weir (m/s)
P = Pool depth below crest (m)

Non-modular flow (submerged): Occurs when the downstream water level influences the upstream water level (Figure 2). In this flow condition both the upstream and downstream water levels need to be gauged in order to determine the discharge over the Crump weir (Sileshi 2009).

The definition sketch (Figure 2) shows the following parameters:

h_2 = Measured water level downstream relative to the weir crest (m)
v_2 = Downstream mean velocity (m/s)
H_2 = Total downstream energy head relative to the weir crest (m)

To prevent non-modular flow conditions from occurring, the downstream water level should be less than 75% of the upstream water level – this is known as the modular limit of the structure. Non-modular flow conditions were beyond the scope of this study.

Requirements for compound crump weir structures

Table 1 discusses the pool depth, Froude number and divider wall requirements for constructing the compound Crump weir structure.

Table 1: Requirements for compound weir structures

Requirement	Details
Pool depth (P)	The minimum pool depth required for accurate gauging is: $P \geq \frac{H_d}{2}$ Where: H_d = Height of the highest measurable water level (m). The pool should extend to a minimum of 5 H_d. (Wessels & Rooseboom 2009)
Froude number (Fr)	For stable flow conditions upstream of the weir variations in the approach, velocity should be limited. Fr < 0.40 (van Heerden *et al* 1986)
Divider wall	According to the BSI 3680 standards, extend horizontally at a 90° angle for a minimum distance of 6 H_d upstream of the weir crest. The wall then extends at a 45° angle until it reaches the floor. Use a thickness of 1 m to avoid sharp curvature in the flow lines at the entrances. The edge of the divider wall should be semi-circular. (Wessels & Rooseboom 2009)

Compound weir structures with and without divider walls

Divider walls are required to separate the different weirs of a compound gauging structure in order to minimise the possibility of three-dimensional flow. Three-dimensional flow includes a horizontal flow velocity component perpendicular to the main velocity vector at the observation point, which contradicts the assumption of parallel flow lines (Wessel & Rooseboom 2009).

Figure 3 illustrates the points at which three-dimensional flow occurs with or without divider walls. In the case of a compound weir with divider walls, the flow lines across the weir are parallel, ensuring accurate gauging of water levels. When compared to the compound weir without divider walls, it is evident that the flow lines are distorted across the weir section where the adjacent weirs meet.

Debris and sediment loads are a problem in South African rivers, resulting in the construction of compound weir structures without divider walls. The presence of divider walls

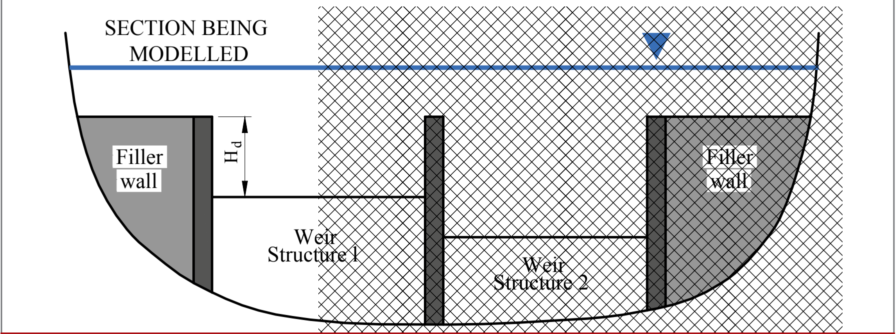

Figure 5: Segment of river being modelled

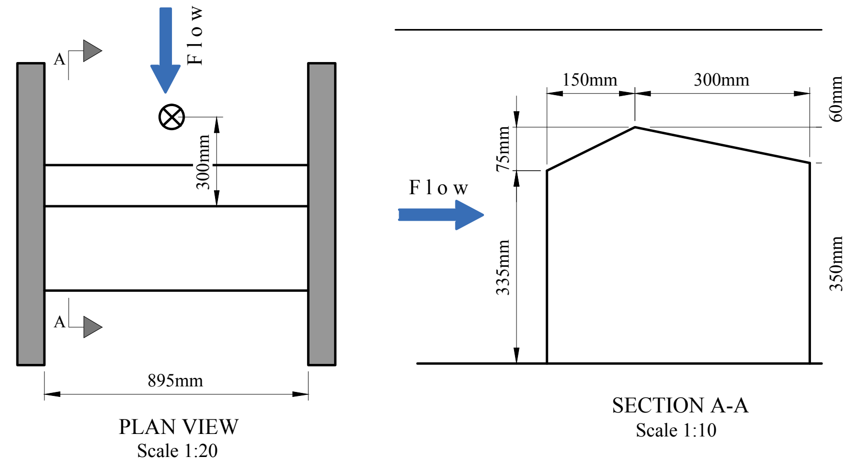

Figure 6: Design drawing of the calibration setup

causes debris to be trapped, resulting in three-dimensional flow patterns.

Overtopping of divider walls

The overtopping of divider walls is an unexplored area of research. Overtopping of a divider wall would result in three-dimensional flow over the crest of a weir. In practice the ends of a compound weir structure are equipped with walls that extend to the side of the river, also known as filler walls. Figure 4 indicates a cross-section of a compound weir with filler walls in a river section.

When the flow in the river section results in the overtopping of the divider walls, the filler walls also start to overtop and thus act as broad-crested weirs. A water level reading upstream of the lowest weir crest is used in practice to calculate the discharge in the river section. For a model study, a water level reading just upstream of the Crump weir is used to calculate the discharge over the Crump weir, while another water level just upstream of the filler wall is used to calculate the discharge over the filler wall. The sum of these two calculated discharges should be equal to the upstream discharge (conservation of mass). If they are not equal, the difference from the calculated upstream discharge indicates that the discharge–head relationship is incorrect (conservation of energy).

EXPERIMENTAL SETUP

A physical model was built at the laboratories of the Department of Water and Sanitation to simulate a compound Crump weir structure with divider walls. The model represents only a segment of what will occur in practice. Figure 5 illustrates the segment, i.e. a Crump weir, a filler wall and a divider wall that are modelled between two plastered brick walls. The experimental work was done in two parts, i.e. the pump calibration and the experimental setup.

Design of pump calibration setup

The setup was used to calibrate the recorded flows from the pumps at the DWS laboratories. The flow rates supplied by the pumps were compared to those calculated using the water level readings. The Crump weir was the full width of the channel, and one water level reading 300 mm upstream of the crest was taken using a point gauge.

Figure 7: Photograph of the calibration setup with annotations

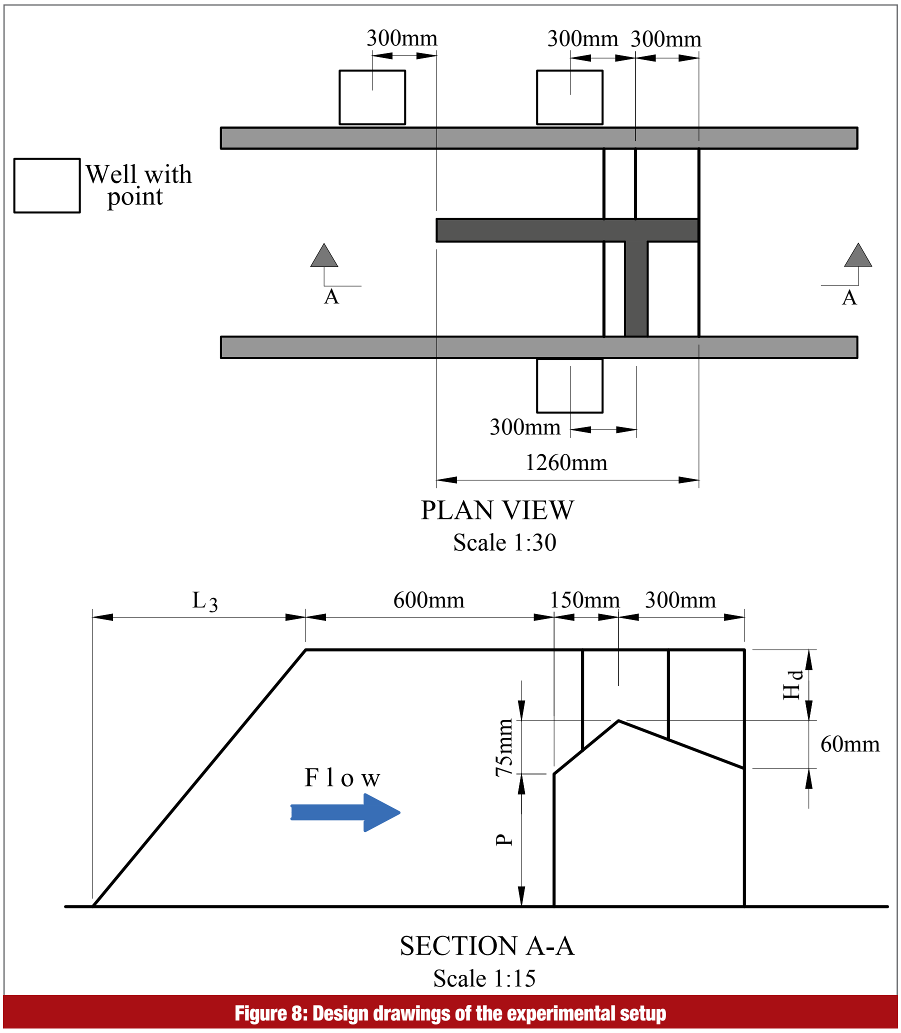

Figure 8: Design drawings of the experimental setup

Figure 6 illustrates the design drawings of the calibration setup.

Figure 7 is a photograph of the model in operation. The model starts off 3 m wide and then narrows to an 895 mm wide channel section. In order to stabilise the flow, 75 mm diameter concrete pipes cut to approximately 300 mm lengths were stacked in front of the outlet pipes.

Design of experimental setup

The experimental setup was varied to depict three different Crump weir lengths, as well as two different pool depths. To determine whether the effect of overtopping of the divider wall differs with increased water levels, the model was tested under different flow conditions. During the course of the experiment water level readings were taken at three different points.

Figure 8 illustrates the design drawings of the experimental setup. The positions of the point gauges (wells) are also indicated in the drawings. The divider wall and the filler wall were designed to be 100 mm thick.

RESULTS AND DISCUSSION

Calibration results

The calibrated results are depicted in Figure 9, the flows measured by the pumps were plotted in relation to the flows calculated using the measured upstream water levels. All three pipes (small, medium and large) were plotted on the

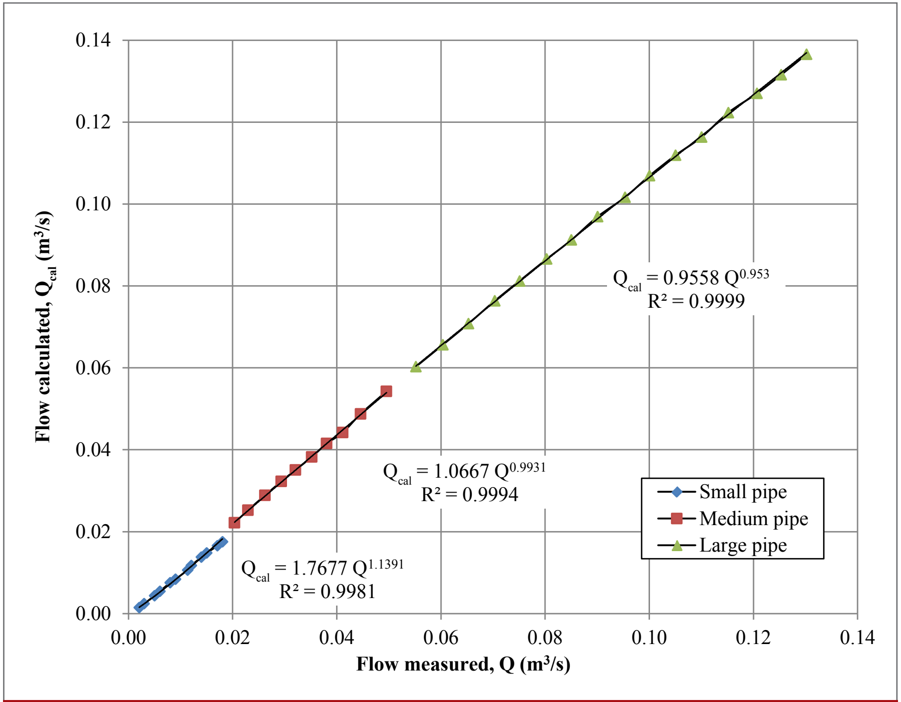

Figure 9: Calibration results

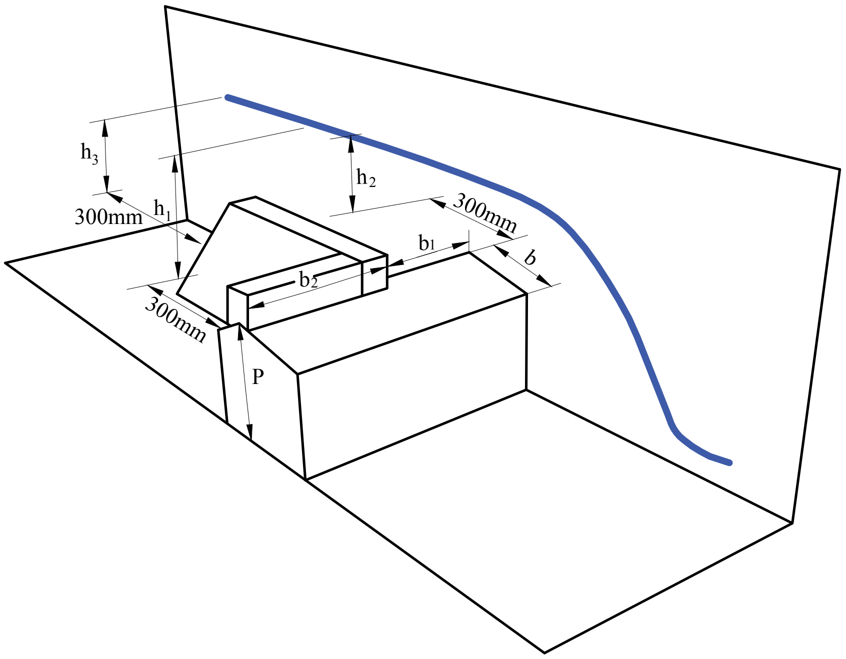

Figure 10: Definition sketch of observation points h_1, h_2 and h_3

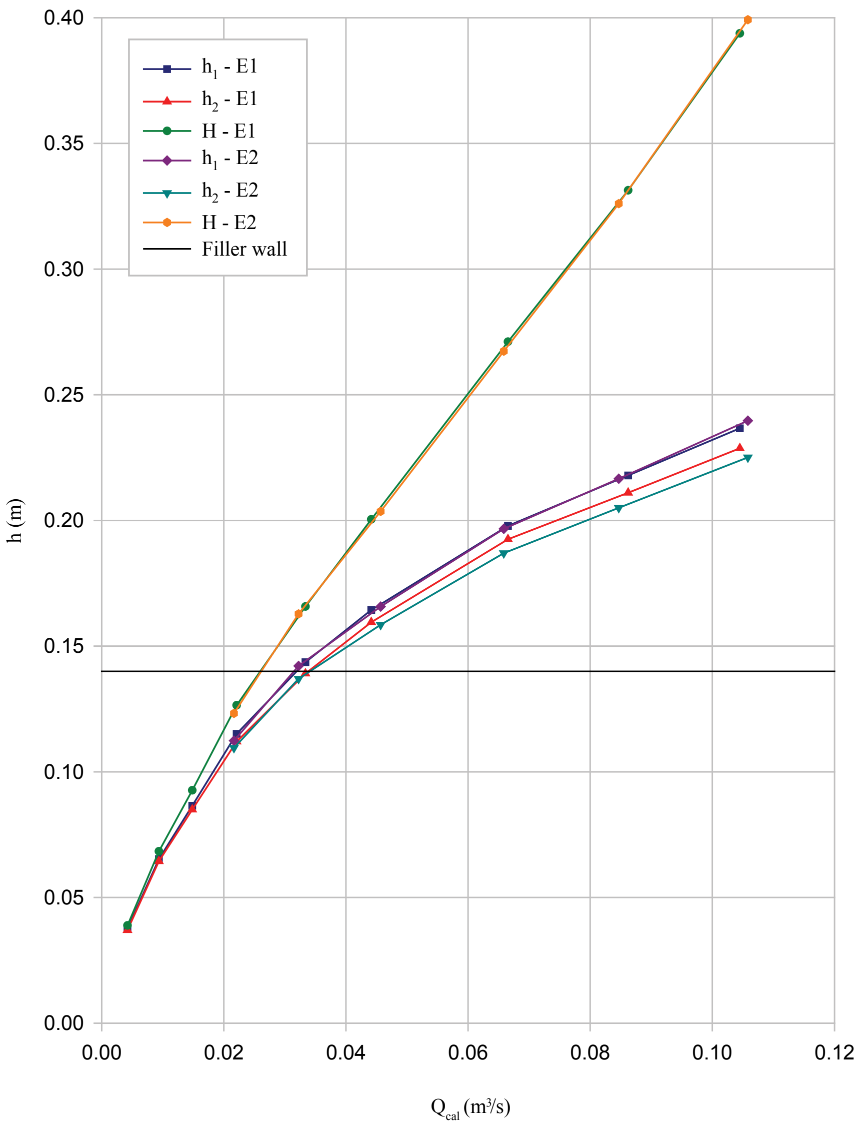

Figure 11: Results for E1 and E2

same graph. Each data set was fitted with a power curve, and the following equations were obtained:

- Small pipe: $Q_{cal} = 1.7677\ Q^{1.1391}$
- Medium pipe: $Q_{cal} = 1.0667\ Q^{0.9931}$
- Large pipe: $Q_{cal} = 0\ 9558\ Q^{0.953}$

These equations were used to adjust the flows measured by the pumps during the experimental setup.

Analysis of experimental results

The results represent water level readings in relation to the calculated energy head. The following three water level readings were observed (see Figure 10):

- h_1 – 300 mm upstream of the filler wall
- h_2 – 300 mm upstream of the Crump crest
- h_3 – 300 mm upstream of the divider wall

The h_3 water level is not measured in practice, but is used in this study to determine the energy level H for each discharge.

Table 2 explains the details of the nine experiments that were performed. The divider wall was raised by 300 mm so that the effects of overtopping of the wall could be studied for two different pool depths.

Figures 11, 12, 13, 14, 15 and 16 indicate the water level readings h_1 and h_2 in relation to the energy level H calculated from the water level reading h_3. The figures depict that the energy level H upstream of the divider wall was not affected by the raise in height of the divider wall. The figures also indicate the level of the filler wall (black line); all water levels above this line indicate overtopping.

It can be noted that the water levels for a shallower pool depth are lower than the water levels for a deeper pool depth. The energy level is, however, higher for a shallower pool, due to the cross-section becoming smaller for the same flows, resulting in an increased flow velocity.

Results for experiments E1 and E2 (Figure 11)

The water level over the Crump weir decreases when the divider wall is raised, and the water level over the filler wall remains approximately the same for both E1 and E2. The higher water level over the Crump weir, when the divider wall is the same height as the filler wall, is as a result of the three-dimensional flow caused by the overtopping of the divider wall. This overtopping induces energy losses downstream of the observation point, hence the water level rises to compensate for the losses. Since the water level over the filler wall remains the same in both tests, the flow over the system will be overestimated.

Results for experiments E3 and E4 (Figure 12)
The water level over the filler wall remains approximately the same for both E3 and E4. However, the water level measured over the Crump weir decreases when the divider wall is raised. The higher water level over the Crump weir results in the flow being overestimated. The water level rises to compensate for the energy losses induced downstream due to overtopping.

Results for experiments E5 and E6 (Figure 13)
The higher water level over the Crump weir, when the divider wall is 100 mm above the weir crest, indicates that the discharge will be overestimated for flows above the structure's capacity.

Results for experiments E7 and E8 (Figure 14)
The water level over the filler wall remains approximately the same for both E7 and E8. However, the water level measured over the Crump weir decreases when the divider wall is raised. The higher water level over the Crump weir, when the divider wall is 100 mm above the weir crest, causes the flow to be overestimated.

Results for experiments E9 and E10 (Figure 15)
The water level over the Crump weir and the water level over the filler wall remained the same for both tests. This indicates that the discharge was unaffected by the overtopping of the divider wall for E7 and E8.

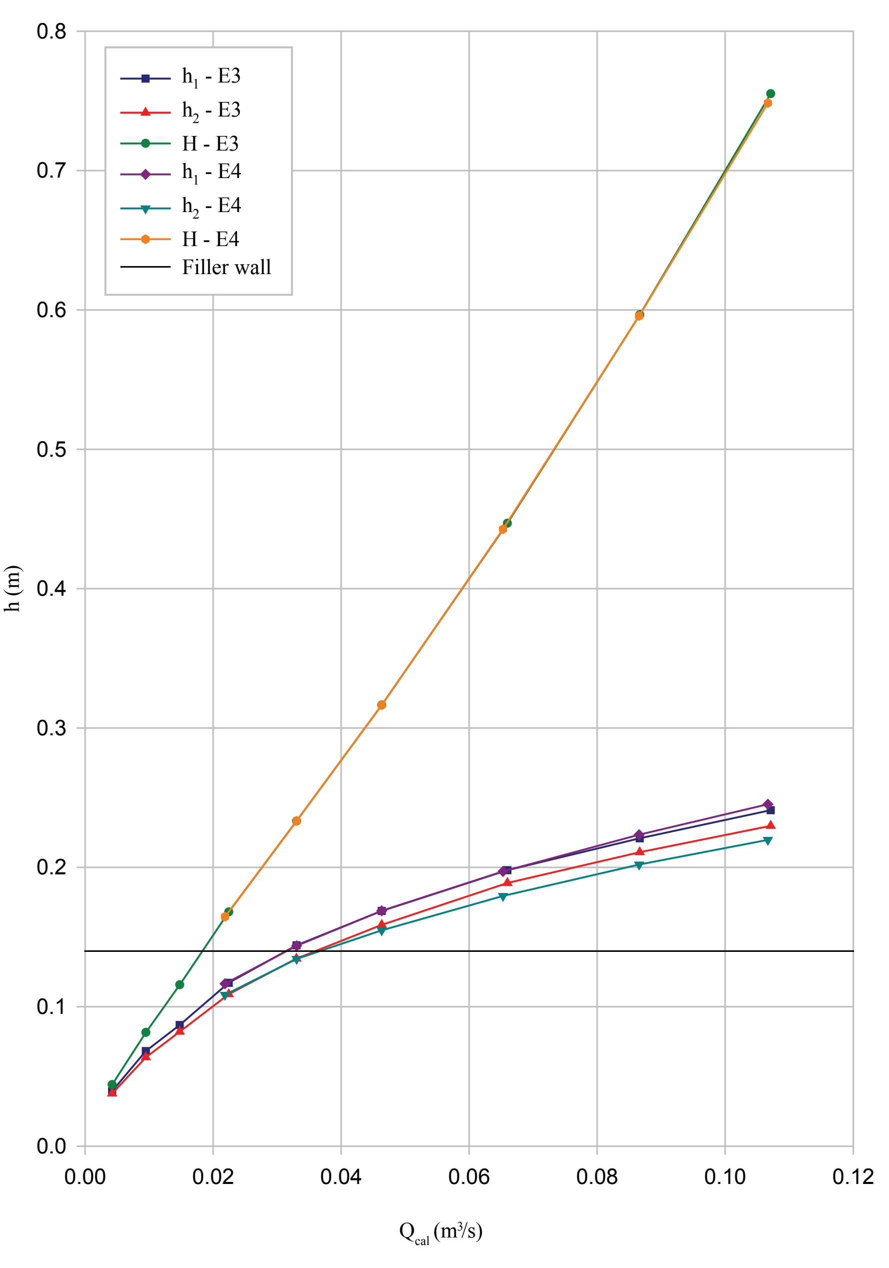

Figure 12: Results for E3 and E4

Table 2: Details of experimental setups

Experiment	Flow rate (ℓ/s)	Crump weir width b_1 (mm)	Filler wall width b_2 (mm)	Divider wall height H_d (mm)	Pool depth P (mm)
E1	5, 10, 15, 20, 30, 40, 60, 80 and 100	288	507	100	410
E2	20, 30, 40, 60, 80 and 100	288	507	400	410
E3	5, 10, 15, 20, 30, 40, 60, 80 and 100	288	507	100	130
E4	20, 30, 40, 60, 80 and 100	288	507	400	130
E5	5, 10, 15, 20, 30, 40, 60, 80 and 100	385	410	100	410
E6	20, 30, 40, 60, 80 and 100	385	410	400	410
E7	5, 10, 15, 20, 30, 40, 60, 80 and 100	385	410	100	130
E8	20, 30, 40, 60, 80 and 100	385	410	400	130
E9	5, 10, 15, 20, 30, 40, 60, 80 and 100	585	210	100	410
E10	40, 60, 80 and 100	585	210	400	410
E11	5, 10, 15, 20, 30, 40, 60, 80 and 100	585	210	100	130
E12	40, 60, 80 and 100	585	210	400	130

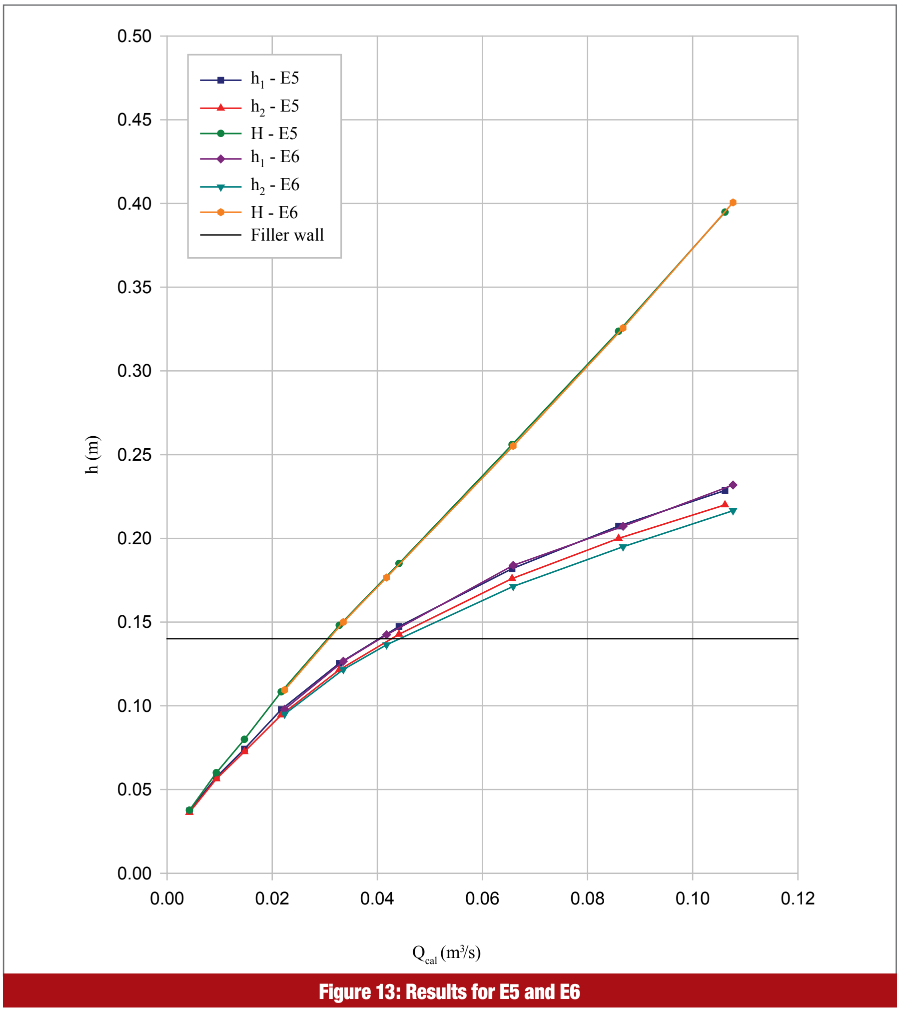

Figure 13: Results for E5 and E6

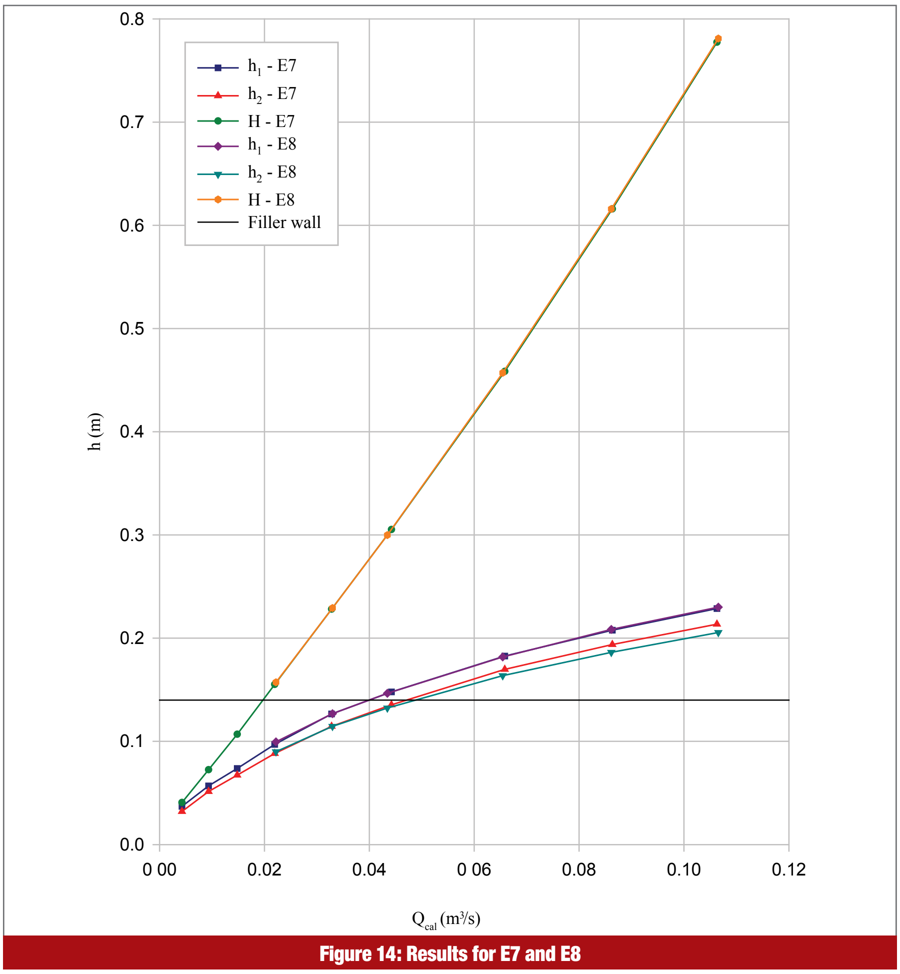

Figure 14: Results for E7 and E8

Results for experiments E11 and E12 (Figure 16)

For E11 the water level over the Crump weir is lower than the water level observed over the filler wall. E12, however, shows that the water levels over the Crump weir and over the filler wall are equal for the tested flow rates. These levels are also equal to the water level over the filler wall observed during E12. The results for the 385 mm Crump weir width differ from the previous two widths.

The calculated flows are underestimated for E11 and E12. This could indicate that the energy losses experienced due to the divider wall are larger than the losses caused by the overtopping. Wessels and Rooseboom (2009) stated that, when divider walls are present, the calculated flow tends to be underestimated. This supports the argument relating to the reason for the drop in water level when the divider wall is 100 mm above the weir crest.

CONCLUSIONS

It can be concluded that the overtopping of the divider wall has an influence on the measured water level upstream of the Crump weir crest.

The results indicate that, for increased water levels over the Crump weir, the effects of overtopping become more significant than for lower flows. The overtopping of the divider wall for narrower Crump weir sections causes the flow to be overestimated. However, for wider sections the turbulence upstream of the observation point becomes the dominant factor resulting in the underestimation of the flow.

RECOMMENDATIONS

Furthering the study is essential for ensuring accurate gauging of flow beyond the structure's capacity. For the continuation of research the following recommendations are made:

- The effects of the overtopping of the divider wall and filler wall should be quantified in order to derive new discharge equations for the calculation of discharge across compound Crump weirs. These new relationships are essential for the accurate measurement of discharge above the design gauging capacity of the compound Crump weirs.
- Test the Crump weir widths that are wider than those considered above. This should be done in

order to investigate the claim that the turbulent flow upstream of the observation point is dominant for wider weir widths.

- The effect of changes in the thickness of the divider wall should be investigated. Higher flow rates should be tested to investigate whether the effects of overtopping of the divider wall become negligible at higher water levels.
- Literature indicates that the Crump weir is relatively insensitive to submergence. This claim should be investigated for testing beyond the structure's capacity. This is a complex condition to analyse, and it is important that the modular conditions are fully understood and quantified before non-modular conditions are studied. As most weirs start to operate under non-modular flow conditions near or just above the structure's design capacity, the impact of downstream water levels on the upstream water level measurements are critical.

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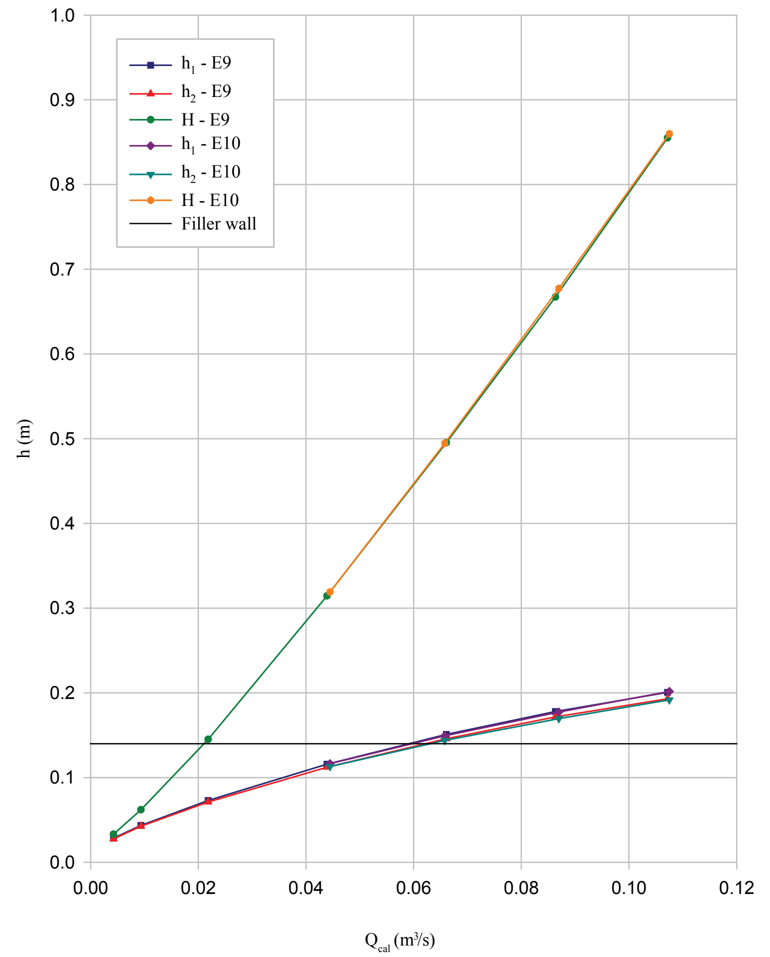

Figure 15: Results for E9 and E10

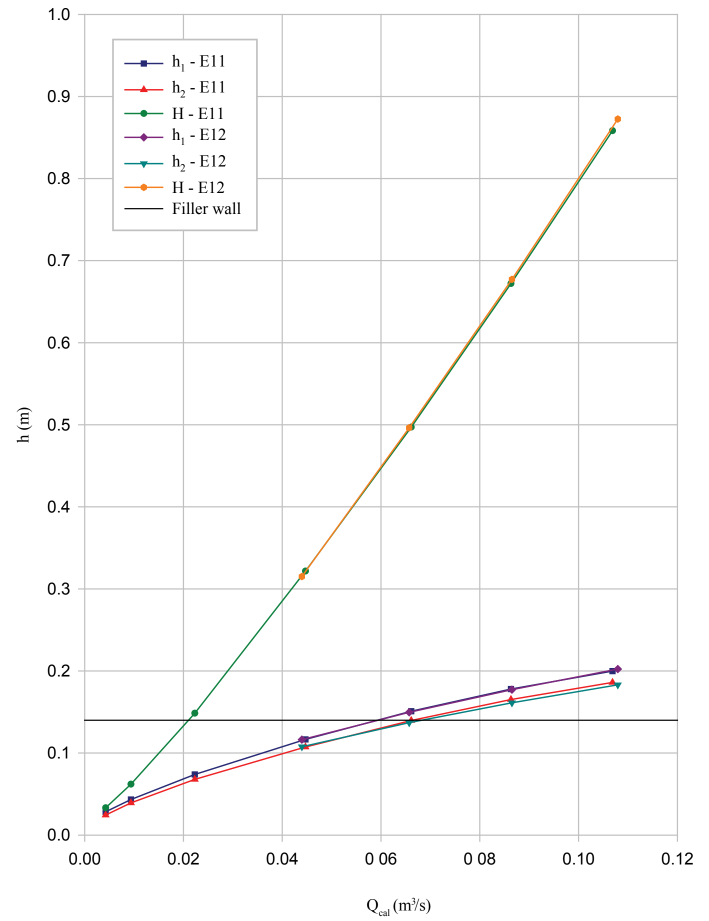

Figure 16: Results for E11 and E12