Combined Surface Channel and Pipe System

Interim Report

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Report SR 585
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Contract - Research

This Interim Report describes work carried out during Stage 2 “Experimental tests” of Highways Agency (HA) Contract No. 3/241 by HR Wallingford Limited in association with Transport Research Laboratory Limited (TRL). The HA Designated Officer for the project is Mr SV Santhalingam. The HR job number is MBS0270. The report is issued as an unpublished document on behalf of the funding organisation. This report was prepared by Ms M Escarameia and Mr RWP May of HR and Mr AJ Todd of TRL.

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Summary

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This Interim Report describes Stage 2 of the research project on combined surface water channels and pipe systems, Experimental Tests. This stage included: hydraulic tests carried out at HR Wallingford and structural tests at the Transport Research Laboratory (TRL).

During the previous stage of the project, Stage 1 (see May et al, 1999) it was determined that, in order to minimise clogging, these systems should not include a continuous slot: instead collecting chambers protected by gratings should be constructed at appropriate intervals along the channel to enable surface water to be discharged into the internal pipe.

The main objective of the hydraulic tests was the determination of head losses in the system, including local head losses created at the collecting chambers, for a range of flow conditions and different geometric configurations of the chambers.

The tests were carried out in a 2.44m wide flume that could be tilted to slopes from zero to 1/40 and that was specifically adapted for the testing of road drainage channels. The flume length was approximately 25m and the total flow capacity was about 180 l/s. Flow from the surface water channel into the collecting chamber was supplied by means of a pipe manifold suspended above the flume. The test arrangement consisted of a section of pipe upstream of a collecting chamber, a section of surface water channel, a collecting chamber and a section of pipe conveying the flow from the chamber. Two different set-ups were tested: Set-up I, where the chamber was in an off-line position in relation to the pipe alignment, and Set-up II, where the chamber was in-line.

Different geometries of the benching inside the chambers were also investigated. From detailed measurements of water depth along the pipe, the energy losses at the chambers were determined and equations were developed to enable the quantification of these losses.

The structural testing of the concrete channel sections was undertaken in accordance with the procedure set out in Clause 517 “Linear Drainage Channel Systems” of the Specification for Highways Work (MCHW1), Clause NG517 and Appendix 5/6 of the Notes for Guidance (MCHW2). From the finite element study and hydraulic analysis reported in Stage 1 of this project, two cross-sections were chosen for structural testing based on an appropriate ratio between the flow capacity of the channel and that of the internal pipe. The nominal bore of the

Summary continued

internal pipe was 500mm with 150mm thick side walls in both test sections; however the base and channel thickness were 100mm for Sample 1 and 150mm for Sample 2. The samples were cast in-situ from Grade C35 concrete to BS5328, that was air entrained in accordance with BS 5931. Failure of both samples occurred much below the expected value (at only 60kN and 115kN, for Samples 1 and 2, respectively).

In addition, structural tests were carried out on two slotted channel/pipe sections obtained from a site on the M1 at Stoney Clouds in Nottinghamshire. The test pieces were cut from a section of the concrete channel that had been slip-formed on site and were then transported to TRL for testing. The nominal diameter of the void was 200mm but closer inspection revealed that in one test piece the diameter was 195mm and in the other it was 210mm, which meant that two different loading procedures were applied according to recommendations in Clause 517. The 195mm diameter block withstood the 400kN load for Class D400, whereas the block with the larger void cracked at 325kN.

The choice of internal pipe diameter appears to be crucial in terms of the structural testing. The loading applied to channels with voids of 200mm or less tends to treat the channel as a cube and, as was observed, the channel edges take much of the load, despite the insertion of packing. Hence the channel only fails when the channel edges crush. The test procedure set out in the MCHW appears to be more appropriate for commercially produced linear drainage channels that have a much smaller cross-sectional area than those tested. Linear drainage channels are often installed into trafficked areas and therefore have to be able to withstand repeated dynamic loading from vehicles. The test procedure may not be wholly appropriate for the present application where the channel is located at the carriageway edge beyond the hard strip or shoulder and hence subject only to occasional or accidental trafficking.

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1. INTRODUCTION

1.1 Background

The overall objective of the project is to develop a design guide for a new type of combined channel and pipe system to be used for draining surface water from trunk roads and motorways. The drainage system will make use of the newly-developed capability of concrete slip-forming machines to construct triangular surface water channels with a circular pipe within the base block, which will increase the drainage capacity of the system.

During Stage 1 of the project, which is described in the Initial Report (May et al, 1999), a review was carried out of the following: (1) data on UK schemes using slip-formed slotted drainage systems; (2) current and future capabilities of slip-forming machines; (3) possible methods of forming the internal pipe; (4) flow capacity of the combined system relative to that of surface water channels; (5) structural strength of the combined system using a numerical finite element analysis; (6) costs of the combined system compared with surface water channels. It was concluded that combined channel and pipe systems represent a viable option and can offer significant advantages in terms of flow capacity, overall cost and convenience. It was also determined that, to minimise the tendency for clogging, the channels should not include a continuous slot but should instead discharge into the internal pipe via grated collecting chambers.

This Interim Report describes work carried out during Stage 2 of the project: Experimental tests.

1.2 Objectives of Stage 2 of the project

The overall objective of Stage 2 was to establish the viability in terms of hydraulic capacity and structural strength of a new drainage system formed by combining a surface water channel with a pipe. Following the assessment made during Stage 1, it was decided to investigate systems where the surface channel is separate from the pipe (as opposed to systems where the surface runoff flows continuously into the pipe through a longitudinal slot along the invert of the channel). An experimental programme consisting of the following types of test was carried out to achieve the above-mentioned objective:

- hydraulic tests (carried out at HR Wallingford, HR)
- structural tests (carried out at the Transport Research Laboratory, TRL).

The tests at HR dealt with the determination of head losses in the system formed by the combined channel and pipe, including the local head losses created at the collecting chambers for a range of flow conditions and different geometric configurations of the chambers.

The work conducted at TRL involved the structural testing of concrete channel and pipe sections to compare with the predictions of the finite element model developed in Stage 1 and highlight any possible constructional problems relating to the formation of a void in the channel block. The results of the tests would also enable the verification of the finite element model and any necessary refinements to be implemented in further simulations.

2. HYDRAULIC TESTS

2.1 Experimental facility

2.1.1 General description of test rig

An existing test facility at HR Wallingford's laboratory, which had been previously adapted for a study of prefabricated linear drainage channels, underwent further modifications for the present tests. This test facility is a 2.44m wide flume that can be tilted to slopes from zero to 1/40. The flume length is approximately 25m and the flow is supplied to an upstream tank by two equal pumps of 152 l/s total capacity. Orifice plates inserted in the pumps' pipework and connected to a manometer board were used to measure the flow rate. A third pump of 28 l/s capacity was also available for use. A schematic layout of the test rig is shown in Figure 1.

Flow from the upstream tank of the test rig (2.44m wide) needed to be contracted gradually to provide smooth flow conditions at the entry into the considerably smaller diameter of the pipes in the combined channel and pipe system. This was achieved by reducing the flume width to 1.2m and then creating a gradual contraction to 0.6m wide. A further smooth contraction was made in concrete at the entry to the upstream end of the test system. The flow from the test pipes was discharged freely into a tank where water levels could be controlled by a tailgate, if necessary.

For the present study the smaller pump (28 l/s capacity) was connected to a pipe manifold suspended above the flume. The flow rate from the pump was measured by means of an electromagnetic flow meter with a voltmeter display. This pipe manifold, which had been designed to convey uniform lateral inflow into linear drainage systems, was used to simulate flows from the surface water channels into the collecting chambers (see Figures 1 and 2). The manifold consisted of a 10m long 150mm diameter plastic pipe with 20 equally spaced ports fitted with valves. These valves were connected to flexible transparent tubes approximately 1.3m long. For the present tests some of the valves were shut to allow flow from the manifold to be concentrated at a particular point in order to simulate the discharge point from the surface water channel. In order to avoid pneumatic effects inside the pipe, air bleed valves were installed at either end of the manifold. The manifold was suspended above the test section from steel portal structures which were fixed to the floor of the laboratory.

The testing arrangement was based on the conclusions of the review stage which suggested that the best option consists of an unslotted channel and pipe system where the two drainage components (the pipe and the surface water channel) are completely separate. The main aspect to investigate was the effect of the extra head loss at the collecting chambers caused by flow discharging from the surface water channel into the pipe system and the subsequent exit from the chamber. Therefore there was no need to reproduce the surface water channel in its entire length. It was sufficient to reproduce the downstream end of the channel and to simulate the water depth and flow at the approach to the chamber.

2.1.2 Description of configurations tested

Stage 1 of the study concluded that unslotted channel/pipe systems were the most viable option to investigate further. This type of arrangement consists of a series of slipformed channel and pipe blocks separated by collecting chambers. At the upstream end of such a system the flow is conveyed by the surface water channel until its capacity is reached, at which point the flow is discharged into a chamber. The flow that enters the chamber is then conveyed by the pipe while the runoff from the next section of road is collected by the channel until its capacity is reached and the flow is discharged into the next chamber (this is illustrated in Figure 3). From a construction point of view it is advantageous to maintain the same pipe diameter along the whole system and therefore the pipe is likely to be flowing part-full until the last outfall chamber in the system. The hydraulic tests were carried out with configurations based on the above description, i.e. configurations consisting of surface water channels discharging at collecting chambers and pipes conveying the flow from one chamber to the next.

Since it was possible in the test facility to change the ratio between flow rates in the channel and the pipe, it was not necessary to reproduce a series of chambers. It was also unnecessary to reproduce the whole channel/pipe block since the flow conditions along the surface water channel were not being studied. The test arrangement therefore consisted of a section of pipe upstream of a collecting chamber, a section of the surface water channel, a collecting chamber and a section of pipe conveying the flow from the chamber. Although this was the overall arrangement, two different set-ups were tested:

Set-up I – This test arrangement was formed by two sections of plastic pipe of 125mm internal diameter, a section of triangular surface water channel and a collecting chamber. Both the channel section and the chamber were reproduced in wood, and perspex windows were included in the chamber to aid the flow visualisation. Figure 4 gives a schematic diagram of this set-up and Plates 1 and 2 show respectively a general view of the test section and the gradual upstream transition.

Set-up II – Use was made of 1metre long prefabricated linear drainage units which included a 125mm diameter void and had a longitudinal slot that allowed the direct measurement of water depths inside the pipe. In this set-up the water from the triangular surface water channel was also discharged into a collecting chamber (i.e. the slot was only used to facilitate the measurements). As in Set-up I, both the channel and the chamber were constructed in wood and a perspex window was incorporated in the chamber for observation purposes. Figure 5 gives a schematic diagram of this set-up and Plate 3 shows a view of the test section from upstream.

The position of the collecting chamber in relation to the alignment of the pipe was different in the two set-ups: the chamber was in an off-line position in Set-up I (i.e. built towards the verge of the carriageway) and in an in-line position in Set-up II. These two alignments reflect the geometries recommended for the outfalls from surface channels. As can be seen in Plates 4 and 5, the design of the collecting chambers followed recommendations given in Advice Note HA78 (DMRB 4.2). Various forms of benching were also introduced inside the chambers in each set-up with the objective of finding the best way of reducing the head losses at the chambers. Information on recommended benching geometries was obtained from the Highway Construction Drawings (MCHW3), namely from Drawing F6 and the types of benching tested are shown in Figure 6. A summary description of the various configurations tested is given in Table 1, which makes reference to Figures 4 to 6 as well as to Plate 6 (to illustrate the most complex benching used in the test programme - Benching I).

As mentioned above, the tests were carried out with pipes of 125mm internal diameter. In real drainage applications, and as demonstrated in the Initial Report (May et al, 1999), it is unlikely that significant flow and economic benefits will be achieved with pipes below, say, 300mm in diameter. This diameter was therefore chosen as the basis for the determination of the geometric scale at which the collecting chambers needed to be designed in the test rig, i.e. 125/300 = 1/2.4. The scale of 1/2.4 and the outfall layouts recommended in HA78 were used to define the geometry of the chambers.

2.1.3 Measuring equipment

For most of the tests the measuring equipment consisted of the following elements:

- orifice plates connected to a manometer board to measure the flow rate into the pipe;
- an electromagnetic flow meter with a voltmeter display to measure the flow rate from the surface water channel discharging into the collecting chamber;
- tapping points connected to electronic point gauges and stilling wells to measure the pressure head along the pipe (this applies to Set-up I – see description of the two different set-ups in Section 2.1.2). The eight tapping points were typically spaced at 1m intervals, with four upstream of the collecting chamber and four downstream. The repeated accuracy of the electronic point gauges was ±0.25mm. For the tests carried out using prefabricated drainage units (Set-up II) which were slotted and therefore allowed direct measurement of water depth, point gauges were installed at four cross-sections along the system to measure the water levels. The measurement positions were: at 0.7m and 1.7m upstream of the chamber and at 2.13m and 2.44m downstream of the chamber.

2.2 Tests

2.2.1 Objectives and test procedure

The main objective of the hydraulic tests was to enable the determination of the head losses in drainage systems that incorporate surface water channels and pipes. It had been established that the two components would operate separately and that they would discharge into intermediate chambers (see Figure 3). The head losses in the pipes are essentially due to friction along the perimeter of the flow and can be determined by established methods (for example by using the Colebrook-White equation presented in tabular form in the HR Tables for the hydraulic design of pipes, sewers, and channels (1998). Similarly, the design of surface water channels and their outfalls is also adequately covered in HA Advice Notes 37 and 78. It was then necessary to determine the head losses caused by the interaction between the flow from the channel and from the pipe at the collecting chambers. A typical channel/pipe system will include a number of chambers and, as mentioned in Section 2.1.2, the system is likely to be designed assuming that the pipes discharging into the chambers will be flowing part-full with water depths that increase towards the downstream end of the system. It should be noted that a system will normally be sized so that it does not surcharge under the specified flow conditions.

The above description implies that the tests would need to be carried out not only for different channel/pipe gradients but also for a range of water depths in the pipe discharging into a chamber and for various ratios of flow in the channel and in the pipe. A comprehensive test programme was therefore carried out to investigate the effects of the following parameters on the local head losses at the chamber:

- relative water depth in the pipe (y/D, where y is the water depth and D is the pipe diameter);
- ratio of flow from the channel discharging into the chamber to the total flow in the pipe immediately downstream of the chamber (Q_c/Q_T);
- channel/pipe gradient;
- geometry of the chamber and its internal benching.

The pipe (and the prefabricated drainage units) were carefully installed in the tilting flume and the flume's tilting mechanism was calibrated prior to the tests to ensure that correct slopes were used in the tests. This was particularly important because most of the tests were carried out with part-full flows where small uncertainties in the measurement of water depths can have a significant effect on the calculation of energy gradients.

In general terms the test procedure involved setting the required flow conditions at the entry into the pipe and at the discharge from the surface water channel. Sufficient time was allowed in each test for the flow to reach steady state conditions before the measurements were taken. These consisted of the two flow rates and the water depths in a number of cross-sections along the pipe. For Set-up I, measurements were taken at four cross-sections upstream of the chamber and at four cross-sections downstream (see Figure 4). For Set-up II water depths were measured at two cross-sections upstream of the chamber and at two cross-sections downstream (see Figure 5).

2.2.2 Test results

As explained in detail in Section 2.3, the water depth measurements were used to determine the energy gradients in the pipe upstream and downstream of the collecting chamber which then allowed the determination of the energy loss coefficient of the chamber. This coefficient was calculated, as is customary in head loss estimations at junctions, in relation to the flow conditions downstream of the chamber, at the first cross-section where measurements were taken (at Tapping Point 4 in Set-up I and Point Gauge 2 in Set-up II - refer to Figures 4 and 5, respectively). Tables 2 to 6 summarise the test results that were considered to be sufficiently accurate to be included in the data analysis. These tables show the slope of the channel/pipe system and the ratio between the flow from the surface water channel and the total flow downstream of the chamber, as well as the values of the water depth and mean flow velocity downstream of the chamber.

Tests were carried out with slopes from flat to 1/50 but, as can be seen in the tables, few tests with very steep slopes offered sufficiently reliable results for incorporation in the data analysis. Part-full flows in pipes at high gradients are affected by the formation of cross-waves and by small disturbances that are easily propagated downstream and amplified. This can create conditions for the localised formation of hydraulic jumps, which cannot be visually detected in closed pipes. For tests where there were major uncertainties regarding the real flow conditions inside the pipe, it was decided not to consider their results in the data analysis.

As can be seen from Table 2, a large number of tests was carried out for Set-up I with Benching I. Plate 7 shows a general view of the test rig during test IBI21 and Plates 8 and 9 illustrate the flow from the surface water channel entering the chamber, viewing from above and from the side, respectively. The flow conditions entering the chamber for Set-up II are shown in Plates 10 and 11, respectively from the top (with gratings removed) and from the side.

2.2.3 Effect of benching inside chambers

As mentioned earlier in Section 2.1.2, the various geometries of benching inside the collecting chambers that were tested are illustrated in Figure 6 and described in Table 1.

Set-up I with Benching I provided the basis for the analysis of the dependency of the local losses at the collecting chamber on the various parameters listed in Section 2.2.1. Benching I was found not to be entirely satisfactory as it allowed the flow to expand too much in the chamber and therefore loose excessive energy. It was therefore decided to improve the benching geometry by taking it to the pipe soffit level (Benching II) and carry out only a few tests with flow conditions similar to those tested with Benching I to enable a comparison of results. Benching III, where the top of the benching was kept level, evolved from Benching II (or IIa) to assess whether the side slopes were beneficial in directing the flow towards the pipe exiting the chamber. Visual observations during the tests did not indicate any significant differences in the flow conditions in the chamber with either Benching II or III.

From the constructional point of view, Benching III has the advantage of having the simplest geometry but further analysis of the test results revealed that Benching II with side slopes of 1/10 appeared to lead to smaller head losses in the chamber. Another advantage of sloping benching is that there will be less tendency for sediment and debris from the road to accumulate on the benching.

2.3 Analysis

2.3.1 Data processing

The data collected consisted mainly of water depth and flow rate readings. The water depth readings from the point gauges were converted into water depths, H, in the pipe and the energy, E, at each of the measuring points was calculated as $H+z+V^2/2g$, where z is the elevation of the measuring point and V is the mean flow velocity in the cross section. This velocity was calculated by dividing the flow rate by the flow area in the cross-section, which was determined from the value of water depth.

With the values of energy along the pipe it was then possible to calculate the energy gradients of the flow upstream and downstream of the chamber for each of the tests. The measuring positions closest to the exit from the collecting chamber were some distance away from the chamber to allow pressures in the flow to return to hydrostatic. This meant that the energy of the flow immediately downstream of the chamber needed to be calculated to allow the determination of the head loss at the chamber. Similarly, the energy of the flow immediately upstream of the chamber needed to be calculated from the value of energy at the measuring point closest to the chamber. The best-fit energy gradients calculated using the experimental data upstream and downstream of the chamber were used for this purpose (i.e. they were extrapolated to the positions at the chamber) and values of chamber energy loss were then calculated (see Column 6 in Tables 2 to 6).

2.3.2 Determination of local loss coefficients at collecting chambers

Local losses, ΔH, such as those produced at collecting chambers are usually determined by the following equation:

$$\Delta H = K\ \left(\frac{V^2}{2g}\right) \qquad (1)$$

where V is a reference velocity, g is the acceleration due to gravity and K is a numerical coefficient that depends essentially on the geometry of the feature under consideration (e.g. bend, junction, tee, etc) and on the flow conditions. The reference velocity is usually taken downstream of the feature in cases of converging flows. This was also the approach adopted in the analysis of the data, where V was, as explained in Section 2.2.2, taken at the downstream measuring position closest to the chamber.

Using Equation (1) and the values of energy loss at the chamber it was possible to calculate the value of K for each of the tests. These values are presented in Column 7 of Tables 2 to 6.

2.3.3 Equations for the determination of losses at collecting chambers

The study of the head losses at the collecting chambers for both set-ups indicated that the single factor most responsible for the losses was whether the flow in the chamber was contained within the pipe benching or expanded laterally into the chamber. When the flow remained within the pipe benching, which occurred mainly for part-full flows, the losses in the chamber were relatively small. When the flow was allowed to expand into the chamber (and contract when exiting it), either because there was no benching or because the energy level of the flow in the pipe was greater than the level of the benching, the losses were relatively higher. For conditions where the flow was essentially contained within the benching, the losses in the chamber were dependent on the relative flow rates in the surface water channel and the pipe. The position of the chamber in relation to the alignment of the combined channel/pipe (in-line or off-line) was found to be of small significance compared to the parameters mentioned above. This can be illustrated by comparing for example the values of K obtained from tests IBII7 and IIBIIa15, in Tables 3 and 5, respectively, which are very similar in spite of the different relative positions of the chambers.

The development of equations for the estimation of the chamber loss coefficients, K, was based mainly on the test results obtained for Set-up I; Set-up II was used to provide general information on the effects of benching in the chamber and on the position of the chamber in relation to the pipe alignment. Set-up I was first tested with Benching I and, as explained in Section 2.2.2, these tests provided the bulk of the data for analysis. Some of the flow conditions in these tests were selected and repeated with Benching II to investigate the expected reduced energy losses with this benching configuration. This analysis procedure is explained next.

It was expected that the relative flow rates coming into the collecting chamber from the surface channel and from the pipe would be an important parameter to consider in the data analysis. For this reason, data corresponding to tests with no flow from the channel were analysed separately from those with channel flow.

For Set-up I with Benching I and no flow from the channel a linear relationship was found between the K values and the relative flow depth in the pipe, y/D, where y is the flow depth downstream of the chamber (see Section 2.2.2) and D is the pipe diameter. Figure 7 shows this relationship for both pipe full and part-full conditions. It should be noted that the point in Figure 7 with a very high value of K corresponded to a test where the pipe was very much surcharged at the entry into the chamber whereas the other full pipe tests had water levels just at or above the pipe soffit. High levels of surcharging are not normally appropriate for the design of combined channel/pipe systems (because of the increased risk of surface flooding onto carriageways and because high pressures can more easily lead to leakages through any cracks or joints between the concrete blocks). Therefore this experimental point was neglected in the determination of the linear relationship. Figure 7 also shows the best fit line to the data, which was determined by linear regression with a correlation coefficient of 0.856. The equation for this line is:

$$K = 1.04\,\frac{y}{D} - 0.476 \qquad \text{for } y/D \geq 0.5 \text{ and Benching I} \qquad (2)$$

where y is the water depth in the pipe and D is the pipe diameter. This equation is valid for $y/D \geq 0.5$; for smaller relative water depths the losses in the chamber can be estimated satisfactorily using the Colebrook-White equation along the length of the chamber.

For conditions where there is flow entering the collecting chamber from both the channel and the pipe, it is reasonable to expect that the chamber losses will be dependent on the ratio of the two flows (or the ratio of flow from the channel to the total flow, Q_c/Q_T). Having established that K depended on y/D for conditions where there was only flow in the pipe, it was also reasonable to expect that a similar dependency would be found for the data with flow from the channel and from the pipe. Figure 8 shows the K values determined for this set of data (Set-up I with Benching I) plotted against Q_c/Q_T for three different ranges of y/D: 0.4 to 0.59, 0.6 to 0.79 and 0.8 to 1.0. It can be seen that K tends to increase with both Q_c/Q_T and y/D, as expected, and that the tests with $Q_c = 0$ provided the lower limit to K for each of the ranges considered. It was then necessary to establish whether a similar behaviour could be found in the test results using the other benching types. Benchings II, IIa or III are benching types in principle more effective at reducing local losses because the flow is contained within the benching for a wider range of flow conditions. The majority of data collected for Benching IIa was consistent with Benching II but was subject to more scatter; it was therefore decided that due to the higher level of accuracy of the data for Benching II, this data set would provide a sounder basis for the analysis. With regard to Benching III, Figure 9 illustrates the higher head loss coefficients obtained from tests with Benching III when compared with Benching II.

When plotting data for Benching II in a similar manner to data for Benching I it was found that the three y/D intervals were not as well defined as before. In fact, data for y/D in the ranges 0.4 to 0.599 and 0.6 to 0.799 could be considered as belonging to the same interval. This is depicted in Figure 10, which also shows the best-fit lines for the two intervals. The corresponding equations are as follows:

$$K = 0.684\,\frac{Q_c}{Q_T} + 0.220 \qquad (3)$$

obtained for $0.520 \leq y/D \leq 0.739$

$$K = 0.714\,\frac{Q_c}{Q_T} + 0.407 \qquad (4)$$

obtained for $0.835 \leq y/D \leq 0.940$

In the above equations Q_c is the flow entering the chamber from the surface water channel, Q_T is the total flow formed by the surface channel and pipe flows and y/D is the relative flow depth inside the pipe downstream of the chamber. In the absence of test results for $y/D<0.520$, the value of K can be determined using Equation 3. This recommendation is based on Figure 8, which shows (for Benching I) that the lower the value of y/D the lower the value of K and therefore the recommendation will provide conservative values.

For determining the head loss at a chamber Equation 1 should be used with the value of flow velocity, V, in the pipe downstream of the chamber and the value of the loss coefficient K given by Equation 2 (if there is no flow from the surface water channel) or by Equations 3 or 4 (if there is flow from the channel).

2.3.4 Hydraulic performance of combined channel and pipe systems

The results of the tests on the collecting chambers will be used in Stage 3 of the project to develop a general method for predicting the flow capacity of combined channel and pipe systems. An analysis will be made to determine how the overall head losses (the sum of the localised losses at the chambers plus the frictional losses along the pipes) compare with an equivalent system in which the flow enters uniformly along its length (as in slotted systems or surface water channels). This will indicate how the existing design method in HA37 (for surface water channels) should be adapted to apply to combined channel and pipe systems.

3. STRUCTURAL TESTS

3.1 Introduction

From the numerical analysis, reported in Stage 1 of this project, two cross-sections were chosen for structural testing with dimensions determined by the size of the testing machine and by the required relationship between the flow capacities of the surface channel and the internal pipe. Both test sections had an internal pipe with a nominal bore of 500mm and 150mm thick side walls, but the base and channel thickness were 100mm for one section and 150mm for the second. The cross-sectional geometry of these blocks is illustrated in Figure 11. Based on the results of Stage 1 (see Section 1.1), it was decided that the sections should be constructed without a vertical slot between the channel and the internal pipe. The test sections were fabricated in the Structures Hall at TRL and had strain gauges cast integrally.

Prior to the construction of the test channel sections, two slotted sections of slip-formed concrete linear drainage channel were obtained from the Balfour Beatty site at Stoney Clouds on the M1 in Nottinghamshire. These sections were approximately 500mm in length and 500mm in both width and depth, had a maximum slot width of 25mm and an internal pipe of nominal diameter 200mm. The width of the top was slightly less than the base due to the inclination of the sides. The voids are believed to have been formed using a ribbed inflatable tube. The depth of the triangular channel was minimal, being only of the order of 25mm. It is believed that the concrete grade was C40.

3.2 Test specification

The testing of all four sections was carried out in accordance with the procedures set out in Clause 517 “Linear Drainage Channel Systems” of the Specification for Highway Works (MCHW1), Clause NG517 and Appendix 5/6 of the Notes for Guidance (MCHW2). The channel sections tested were compliant with Figure 2: System with closed profile and continuous or intermittent slot on top, where the depth of the internal void is equal to, or greater than, the width.

The channels are classified as shown in Section 4 of BS EN 124: Gully tops and manhole tops for vehicular and pedestrian areas (BS EN 124), for the locations set out in Section 5 and shown in Figure 9a: “Typical highway cross-section showing the location of some installation groups” of that document.

The test loads are set out in Table 6 of BS EN 124, with those considered in this project being for classes C250, D400 and E600. The test loads were applied to the channel sections through a loading block dimensioned in accordance with Table 1: Dimensions of Test Blocks in Appendix 5/6 of Notes for Guidance clause NG517.

3.3 Test procedure

According to the test specification, the size of the loading block is dependent on the diameter of the internal void within the channel. Where the diameter or width of the void is 200mm or less, the load must be applied through a block that is 500mm long by the width of the channel section, shown as ‘x’ in Figure 2. There is no guidance as to whether this is the top or base dimension in cases where the sides are inclined to the vertical. Where the diameter is 201mm or greater, the block is required to be 500mm long by 200mm wide.

The test loads were applied using the 600 tonne Losenhausen machine in the Structures Hall at TRL, shown in Plate 1 of Appendix A. The machine is equipped with a ball-jointed top platen to ensure that the load is evenly applied and to take account of any eccentricity in the channel section. The void between the loading block and the top of the channel was packed with a compressible material to ensure a firm seating and parallelism of the longitudinal edges of the test block.

The load was applied vertically by means of a hydraulically-actuated ram at a rate of 2 ± 1kN/s until the test load in BS EN 124 was reached, after which the load was released.

3.4 Tests on slotted channels from Stoney Clouds, M1 Nottinghamshire

This section describes the testing regime undertaken on the two slotted channel sections obtained from a site believed to be on the M1 at Stoney Clouds in Nottinghamshire.

The test pieces had been cut from the slip formed concrete slotted channel drain on site and transported to TRL for testing. Consequently the underside of the test pieces was very rough, having been cast directly on to the Type 1 sub-base, some of which was embedded in the base of each test piece. This questions the method of sub-surface drainage that was used in conjunction with the channel drain. As much of the Type 1 material as possible was scabbled off the base of each test piece. Then an epoxy mortar layer was applied so that a smooth surface was created, to eliminate any point loading of the base.

The nominal diameter of the voids within the sections was 200mm, though on inspection the minimum diameter was found to be 195mm and the maximum 210mm. It was therefore decided to test the two sections using the alternative sizes of loading block described in Section 3.3. The section with the 195mm void was loaded using a 500mm x 500mm block. In lieu of any guidance on this issue, the width of the block was assumed to be that of the base. The section with the 210mm void was loaded using a 200mm x 500mm block.

3.4.1 Section 1: 195mm diameter void

The test piece with the smaller diameter was loaded into the machine and compressible filler was positioned in the channel but covering the complete surface area. The 500mm x 500mm loading block was then positioned and the top loading platen brought down to bear on the loading block. The load was applied vertically at a rate of 2 ± 1 kN/s.

Plate 12 shows the smaller diameter channel section and the 500mm x 500mm block set up in the 600T Losenhausen machine.

This section easily reached the 400kN load for Class D400 with no sign of distress. Rather than release the load, loading continued until the channel block crushed at 1440kN (see Plate 13).

3.4.2 Section 2: 210mm diameter void

The remains of the first section were removed from the machine and the second section installed as shown in Plate 14. The test piece was positioned with the slot running from front to back and the loading block placed with the long side parallel to the slot. Again compressible filler was placed in the channel and the loading block placed on top. Loads were then applied at the same rate as in the first test.

At 325kN a tension crack started to appear at the springing level on one side. As the applied load increased the crack gradually opened with a second crack forming on the opposite side at 735kN. The load continued to be applied until the channel section failed completely, as shown in Plate 15, at 940kN.

3.5 TRL manufactured test pieces

3.5.1 Introduction

Following on from the Finite Element analysis that was undertaken in Stage 1 of the project, two samples of channel were constructed at TRL, based on the indicated maximum pipe size and minimum wall thickness. Because of the decision at the end of Stage 1 to eliminate the slot from the channel and instead proceed on the basis of discrete gully entries at regular intervals, both test pieces had a continuous channel.

Both samples were formed with a 500mm diameter pipe and had a vertical wall thickness of 150mm, thus giving an overall width of 800mm which is the maximum horizontal dimension of specimen that can be installed in the 600 tonne Losenhausen machine. In accordance with the procedure set out in the Notes for Guidance on the Specification for Highway Works (MCHW2), the test samples were 500mm in length.

Only the vertical dimension varied such that one sample had 100mm cover top and bottom to the pipe, while in the other the cover was 150mm.

The samples were cast in-situ from Grade C35 concrete (to BS5328), that was air entrained in accordance with BS 5932. The coarse aggregate was partially crushed as required in Clause 1103 of the SHW (MCHW1). Concrete cubes were taken during the casting of the test samples and three of these were crushed after 7 and three after 14 days. These gave average concrete strengths of 45.7 N/mm^2 and 61.5 N/mm^2 respectively.

Strain gauges were installed in both the external and internal faces of the samples at the 0^o, 90^o and 180^o positions and with 40mm cover.

Strain gauges 1 and 4 were positioned at the 0^o point, 2 and 5 at the 90^o point with 3 and 6 located at 180^o. The lower numbers were on the inside adjacent to the pipe and the higher numbers on the outside.

3.5.2 Test procedure

The procedure is set out in paragraph 20 of Clause 517 “Linear drainage channels” in the Specification for Highway Works (MCHW1) and the Notes for Guidance (MCHW2). A vertical load must be applied through the loading block to the centre of the channel. The load must be applied at a rate of 2 ± 1 kN/s until the specified test load has been achieved. The channels were intended to comply with Class D400 loading (BS EN 124), and hence should maintain a load of 400 kN without failure.

The load was applied through a loading block 500mm long by 200mm wide in accordance with the detail shown in Table 1 of the sample Appendix 5/6 in the Note for Guidance. In the first test (described in Section 3.5.3) the load was applied directly to the block via the loading platen of the machine. In the second instance, a load cell was positioned between the platen and the block. For the first test the loading block was set up on compressible filler to ensure an even pressure distribution. For the second test, the block was set on sand, retained in the “V” of the channel by means of rapid hardening mortar placed at either end of the channel.

The six strain gauges, together with a dummy gauge, were connected to a Scorpio data logger as was the load cell used in the second test.

3.5.3 Sample 1: 500mm diameter void and 100mm top cover

The sample with the 100mm cover to the top of the pipe was placed in the test machine and the strain gauges were connected to the data logger. Compressible filler was placed in the channel and the loading block positioned above this. The loading platen was lowered into place and the load was then applied at the prescribed rate with strain gauge readings being taken at 5kN intervals. However at 60 kN the sample failed in a typical four-hinge mode.

As a consequence of the rapid and unexpected failure of the test piece, virtually no usable data was recovered.

3.5.4 Sample 2: 500mm diameter void and 150mm top cover

The sample with the 150mm cover to the top of the pipe was placed in the test machine and the strain gauges connected to the data logger (see Plate 16). Fine sand was then placed in the channel and the loading block bedded down to compress the sand. The sand was prevented from flowing from beneath the block by sealing both ends of the channel with epoxy mortar. The block did not impinge on the mortar and excess sand was removed from the edges of the block.

In this test a load cell was placed between the loading block and the platen and connected to the data logger.

The load was again applied at the prescribed rate and strain gauge and load cell data were constantly recorded. The strain gauge information is shown in the Appendix.

Again failure occurred rapidly, in this case at around 115kN, and in a four-hinge configuration (see Plate 17). The maximum load applied was 117kN but at this point the test piece had started to collapse rapidly. The maximum tension was recorded at gauge 1 located at the crown of the pipe.

4. CONCLUSIONS AND RECOMMENDATIONS

4.1 Hydraulic capacity

An extensive series of tests was carried out to investigate the hydraulic performance of a new type of channel/pipe system for road drainage discharging separately at collecting chambers. In particular the study was concerned with determining the head losses produced by discharge from the combined surface water channel/pipe system into the chambers. Two types of chamber alignment were tested (in-line with the channel/pipe system and off-line) as well as various geometries of benching inside the chambers. The tests consisted essentially in the measurement of the energy gradient for a range of different ratios of flows in the channel and in the pipe. These led to the development of equations (Equations 2 to 4 to be used in conjunction with Equation 1) that allow the determination of head loss coefficients, K, at the collecting chambers.

The head loss coefficient at the chamber was found to depend mainly on the following parameters: the ratio between the flow rate entering the chamber from the surface water channel and the total flow rate in the pipe immediately downstream of the chamber; and the relative flow depth inside the pipe downstream of the chamber.

The test results showed that the relative position of the chambers with regard to the channel/pipe system (in-line or off-line) had little impact on the head losses at the chamber, with the benching inside the chamber being the most important geometric factor. It is important to set the lower benching level to coincide with the soffit level of the pipe exiting from the chamber in order to avoid flow expansion and associated head losses. Benching II, illustrated schematically in Figure 6 was found to produce the lowest head losses in the chamber and is therefore recommended for design.

4.2 Structural tests

The choice of internal pipe diameter would appear to be crucial in terms of the testing. The loading applied to channels with voids of 200mm or less tends to treat the channel as a cube and, as was observed, the channel edges take much of the load, despite the insertion of packing. Hence the channel only fails when the channel edges crush.

The more severe test appears to be the one applied to channels when the void is 201mm or larger. The block, being only 200mm wide, applies the load towards the centre of the channel such that tension, rather than compression forces, occur in the vertical faces. This is because the top of the channel to either side of the crown of the pipe acts as a cantilever.
The assumption is that the test piece has failed as soon as a crack develops; however, the channel sections with the smaller diameter pipes can withstand considerably greater loads before complete failure occurs.

The test pieces with the large diameter void performed less well than had been predicted by the numerical finite element analysis. The reason for this appears to be linked to the complex way in which the loading is transferred to the sloping sides of the V-channel in the actual tests. The numerical model assumes a simple uniformly distributed load and therefore does not indicate the tension failures that occur in practice. The introduction of reinforcement would help to resist tension failure of the concrete but the greater cost would be likely to make the combined channel/pipe system less cost-effective.

In order to increase strength of the cross-sections, the thickness of concrete cover around the internal pipe is recommended to be a minimum of half the pipe diameter. However, more structural tests and numerical analysis will be needed to establish whether this interim recommendation is valid.

The test procedure set out in the MCHW appears to be more appropriate for commercially produced linear drainage channels that have a smaller cross sectional area than those tested. These channels are often installed in trafficked areas and therefore have to be able to withstand repeated dynamic loading from vehicles. The procedure may not be wholly appropriate in this instance where the channel is located at the carriageway edge beyond the hard strip or shoulder and hence subject only to occasional or accidental trafficking.

5. SCOPE OF WORK FOR STAGE 3

The structural tests carried out under Stage 2 identified an important problem in the application of existing specifications for structural testing (see Section 4.2). This was discussed with the Highways Agency Project Officer. It was agreed that further structural tests and numerical simulations using the finite element model will be required to clarify the current uncertainties.

Stage 3 will be divided into two phases. Based on the results of the hydraulic experiments, the first phase will involve the development of a general hydraulic design method for determining the flow capacity of combined channel/pipe systems and required outlet spacings. The method will extend the results of the tests, which were carried out with steady-state conditions, and will take into account the time-varying characteristics of the flow in the system. In order to be consistent with the method in Advice Note HA 37, the general design method will be based on kinematic wave theory which allows the time-varying effects of storage and rainfall to be correctly described. The second phase of Stage 3 will consist in the preparation of an Advice Note covering geometric factors and limitations on the sizes of channel and pipe, constructional issues, hydraulic design and maintenance requirements.

A Project Report will also be produced giving all the background information from the study and providing a technical reference for the Advice Note.

6. ACKNOWLEDGEMENTS

The authors would like to thank the contribution of Ms Isabel Garcia Hermosa, who assisted with the hydraulic tests during her training placement at HR Wallingford, and Mr Yann Gasowski who helped supervise the experimental work.

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Tables

Table 1 Summary of configurations in the hydraulic tests

ARRANGEMENT	COLLECTING CHAMBER ALIGNMENT	BENCHING * (see Figure 6)
Set-up I (see Figure 4)	Off-line	Benching I
		Benching II
Set-up II (see Figure 5)	In-line	No Benching
		Benching IIa
		Benching III

*General description of benching:

Benching I The benching was taken to the mid pipe diameter level and sloped gently both towards the chamber side walls and towards the downstream wall to direct the flow from the surface channel into the pipe section downstream (see Plate 6).

Benching II The benching was taken to the soffit level of the pipe and sloped from the pipe to the chamber side walls at a slope of 1:10.

Benching IIa Similar to Benching II but the slopes were steeper at 1:5.

Benching III The top of the benching was kept horizontal and set at soffit pipe level.

Table 2 Test results for Set-up I, Benching I

Test (1)	Slope (2)	Q_c/Q_T (3)	Water depth d/s of chamber (m) (4)	Mean flow velocity d/s of chamber (m/s) (5)	Energy loss at chamber (m) (6)	K (7)
IBI1	Flat	0.170	0.075	0.507	0.005	0.42
IBI2	Flat	0.200	0.089	0.582	0.008	0.47
IBI3	Flat	0.370	0.067	0.606	0.007	0.37
IBI4	Flat	0.420	0.091	0.656	0.010	0.44
IBI5	Flat	0.460	0.068	0.531	0.007	0.48
IBI6	Flat	0.430	0.080	0.583	0.009	0.52
IBI7	1/1000	0.190	0.076	0.615	0.006	0.33
IBI8	1/1000	0.170	0.078	0.617	0.008	0.41
IBI9	1/1000	0.320	0.079	0.632	0.011	0.54
IBI10	1/1000	0.320	0.077	0.623	0.010	0.53
IBI11	1/1000	0.480	0.077	0.617	0.012	0.61
IBI12	1/1000	0.500	0.079	0.625	0.014	0.69
IBI13	1/500	0.340	0.088	0.705	0.014	0.55
IBI14	1/500	0.300	0.075	0.723	0.012	0.47
IBI15	1/500	0.190	0.075	0.708	0.009	0.36
IBI16	1/500	0.200	0.082	0.752	0.012	0.40
IBI17	1/500	0.190	0.104	0.804	0.018	0.56
IBI18	1/500	0.470	0.082	0.684	0.015	0.63
IBI19	1/500	0.490	0.074	0.877	0.025	0.64
IBI20	1/200	0.190	0.065	0.956	0.003	0.07
IBI21	1/200	0.230	0.078	1.221	0.024	0.31
IBI22	1/200	0.200	0.067	0.983	0.004	0.08
IBI23	1/200	0.330	0.066	0.949	0.009	0.19
IBI24	1/200	0.350	0.068	0.927	0.013	0.31
IBI25	1/200	0.310	0.074	1.287	0.017	0.20
IBI26	1/200	0.510	0.064	0.935	0.013	0.29
IBI27	1/200	0.520	0.064	0.910	0.023	0.55
IBI28	1/100	0.210	0.063	1.108	0.037	0.59
IBI29	1/100	0.330	0.068	1.204	0.011	0.15
IBI30	1/60	0.190	0.078	1.492	0.012	0.11
IBI31	Flat	0	0.091	0.573	0.008	0.48
IBI32	Flat	0	0.076	0.500	0.004	0.30
IBI33	1/1000	0	0.076	0.649	0.002	0.07
IBI34	1/1000	0	0.077	0.590	0.001	0.08
IBI35	1/500	0	0.074	0.724	0.002	0.09
IBI36	1/500	0	0.083	0.765	0.002	0.07
IBI37	1/60	0	0.066	1.592	0.017	0.13
IBI38	1/60	0	0.073	1.631	0.016	0.12
IBI39	Flat	0.170	0.122	0.737	0.022	0.80
IBI40	Flat	0.220	0.120	0.755	0.023	0.80
IBI41	Flat	0.330	0.116	0.769	0.028	0.94
IBI42	1/1000	0.190	0.115	0.740	0.026	0.94
IBI43	1/1000	0.290	0.117	0.795	0.026	0.81
IBI44	1/1000	0.340	0.112	0.773	0.027	0.87

Table 2 Test results for Set-up I, Benching I (Continued)

Test (1)	Slope (2)	Q_c/Q_T (3)	Water depth d/s of chamber (m) (4)	Mean flow velocity d/s of chamber (m) (5)	Energy loss at chamber (m) (6)	K (7)
IBI45	1/500	0.200	0.115	0.793	0.025	0.78
IBI46	1/500	0.430	0.097	0.745	0.022	0.77
IBI47	1/100	0.150	0.080	1.384	0.025	0.26
IBI48	Flat	0	0.123	0.756	0.019	0.65
IBI49	1/1000	0	0.125	0.925	0.046	1.06
IBI50	1/1000	0	0.120	0.866	0.019	0.50
IBI51	1/500	0	0.117	0.914	0.014	0.34
IBI52	1/200	0	0.113	1.038	0.026	0.47
IBI53	1/100	0	0.108	1.209	0.032	0.43

Table 3 Test results for Set-up I, Benching II

Test (1)	Slope (2)	Q_c/Q_T (3)	Water depth d/s of chamber (m) (4)	Mean flow velocity d/s of chamber (m/s) (5)	Energy loss at chamber (m) (6)	K (7)
IBII1	1/1000	0	0.117	0.965	0.016	0.34
IBII2	1/500	0	0.073	0.738	0.003	0.11
IBII3	1/200	0	0.104	1.106	0.008	0.12
IBII4	Flat	0.360	0.077	0.571	0.012	0.75
IBII5	1/1000	0.190	0.078	0.617	0.009	0.45
IBII6	1/1000	0.190	0.111	0.767	0.016	0.54
IBII7	1/1000	0.340	0.109	0.791	0.021	0.65
IBII8	1/500	0.200	0.085	0.735	0.004	0.14
IBII9	1/500	0.200	0.111	0.821	0.019	0.55
IBII10	1/500	0.420	0.092	0.796	0.017	0.53
IBII11	1/500	0.240	0.072	0.695	0.011	0.43
IBII12	1/500	0.260	0.065	0.708	0.008	0.31
IBII13	1/500	0.500	0.071	0.931	0.013	0.29
IBII14	1/500	0.500	0.070	0.665	0.015	0.68

Table 4 Test results for Set-up II, No Benching

Test (1)	Slope (2)	Q_c/Q_T (3)	Water depth d/s of chamber (m) (4)	Mean flow velocity d/s of chamber (m/s) (5)	Energy loss at chamber (m) (6)	K (7)
IINB1	Flat	0	0.069	0.311	0.001	0.21
IINB2	Flat	0.380	0.080	0.378	0.003	0.46
IINB3	Flat	0.434	0.084	0.394	0.003	0.38
IINB4	1/1000	0	0.076	0.392	0.003	0.34
IINB5	1/1000	0.380	0.076	0.404	0.005	0.63
IINB6	1/1000	0.464	0.082	0.428	0.004	0.41
IINB7	1/500	0	0.075	0.360	0.008	1.27
IINB8	Flat	0	0.108	0.502	0.011	0.87
IINB9	Flat	0.248	0.103	0.448	0.011	1.13
IINB10	Flat	0.356	0.102	0.446	0.010	1.02
IINB11	1/1000	0	0.109	0.540	0.014	0.97
IINB12	1/1000	0.236	0.103	0.469	0.015	1.36
IINB13	1/1000	0.318	0.103	0.514	0.015	1.09
IINB14	1/500	0	0.108	0.558	0.020	1.26
IINB15	1/500	0.190	0.102	0.592	0.016	0.89
IINB16	1/500	0.295	0.101	0.501	0.019	1.49

Table 5 Test results for Set-up II, Benching IIa

Test (1)	Slope (2)	Q_c/Q_T (3)	Water depth d/s of chamber (m) (4)	Mean flow velocity d/s of chamber (m/s) (5)	Energy loss at chamber (m) (6)	K (7)
IIBIIa1	Flat	0.417	0.080	0.348	0.003	0.49
IIBIIa2	Flat	0.472	0.083	0.365	0.005	0.80
IIBIIa3	1/1000	0.417	0.075	0.376	0.007	0.92
IIBIIa4	1/1000	0.434	0.080	0.415	0.008	0.95
IIBIIa5	1/1000	0.464	0.082	0.429	0.009	0.94
IIBIIa6	1/500	0.380	0.077	0.397	0.013	1.59
IIBIIa7	1/500	0.434	0.081	0.412	0.013	1.46
IIBIIa8	1/500	0.464	0.083	0.422	0.013	1.45
IIBIIa9	Flat	0	0.105	0.548	0.008	0.50
IIBIIa10	Flat	0.392	0.100	0.483	0.009	0.73
IIBIIa11	Flat	0.276	0.102	0.589	0.004	0.21
IIBIIa12	Flat	0.296	0.101	0.535	0.008	0.53
IIBIIa13	Flat	0.283	0.102	0.502	0.007	0.54
IIBIIa14	Flat	0.214	0.104	0.512	0.009	0.67
IIBIIa15	1/1000	0.347	0.102	0.533	0.010	0.66
IIBIIa16	1/1000	0.288	0.103	0.542	0.009	0.59
IIBIIa17	1/1000	0.204	0.105	0.538	0.010	0.67
IIBIIa18	1/500	0.360	0.101	0.512	0.017	1.30
IIBIIa19	1/500	0.311	0.101	0.515	0.017	1.25
IIBIIa20	1/500	0.203	0.104	0.569	0.015	0.92
IIBIIa21	1/200	0.315	0.096	0.620	0.033	1.71
IIBIIa22	1/200	0.264	0.100	0.634	0.032	1.54
IIBIIa23	1/200	0.178	0.100	0.665	0.032	1.41
IIBIIa24	1/100	0.164	0.059	1.28	0.024	0.29
IIBIIa25	1/100	0.231	0.058	1.31	0.026	0.30
IIBIIa26	1/60	0.147	0.063	1.33	0.050	0.56
IIBIIa27	1/60	0.186	0.061	1.36	0.042	0.44
IIBIIa28	1/60	0.211	0.062	1.32	0.044	0.49

Table 6 Test results for Set-up II, Benching III

Test (1)	Slope (2)	Q_c/Q_T (3)	Water depth d/s of chamber (m) (4)	Mean flow velocity d/s of chamber (m/s) (5)	Energy loss at chamber (m) (6)	K (7)
IIBIII1	Flat	0.223	0.101	0.514	0.007	1.13
IIBIII2	Flat	0.292	0.101	0.482	0.008	1.02
IIBIII3	1/1000	0	0.109	0.592	0.008	0.57
IIBIII4	1/1000	0.187	0.106	0.562	0.008	0.90
IIBIII5	1/1000	0.261	0.102	0.534	0.008	0.55
IIBIII6	1/500	0.195	0.104	0.562	0.016	0.85
IIBIII7	1/500	0.236	0.104	0.579	0.012	0.82
IIBIII8	1/200	0	0.099	0.707	0.033	1.23
IIBIII9	1/200	0.164	0.100	0.689	0.031	0.98
IIBIII10	1/200	0.218	0.096	0.669	0.032	1.38
IIBIII11	1/200	0.279	0.097	0.625	0.032	1.22

Figures

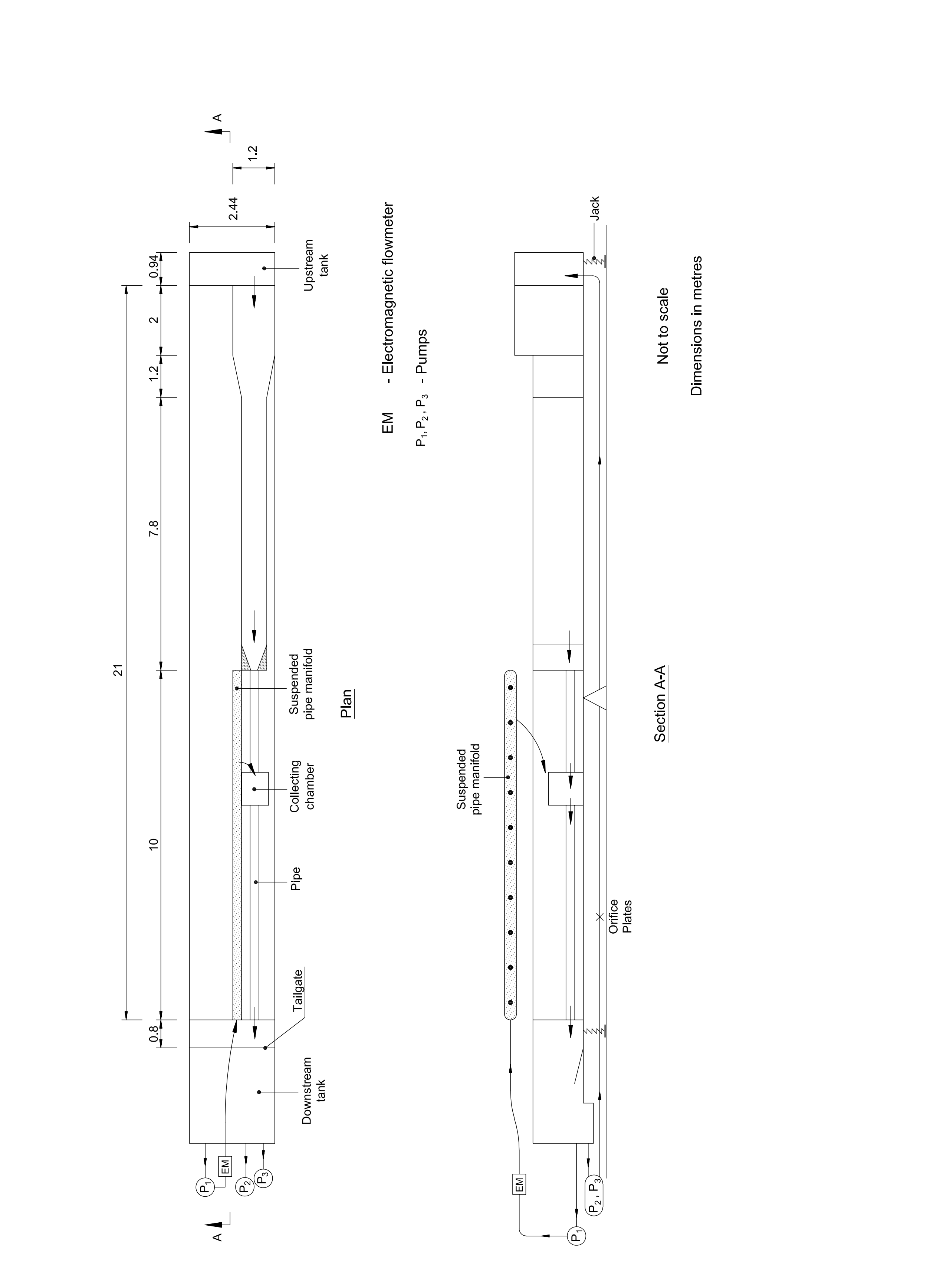

Figure 1 Schematic layout of HR's test rig. Plan view

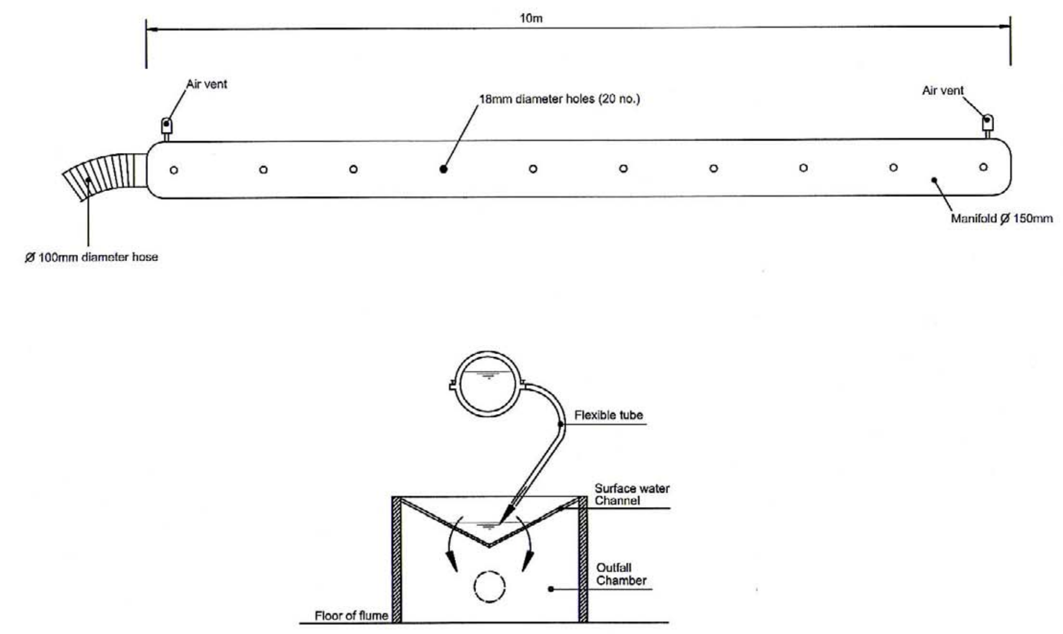

Figure 2 Pipe manifold and supply to surface water channel

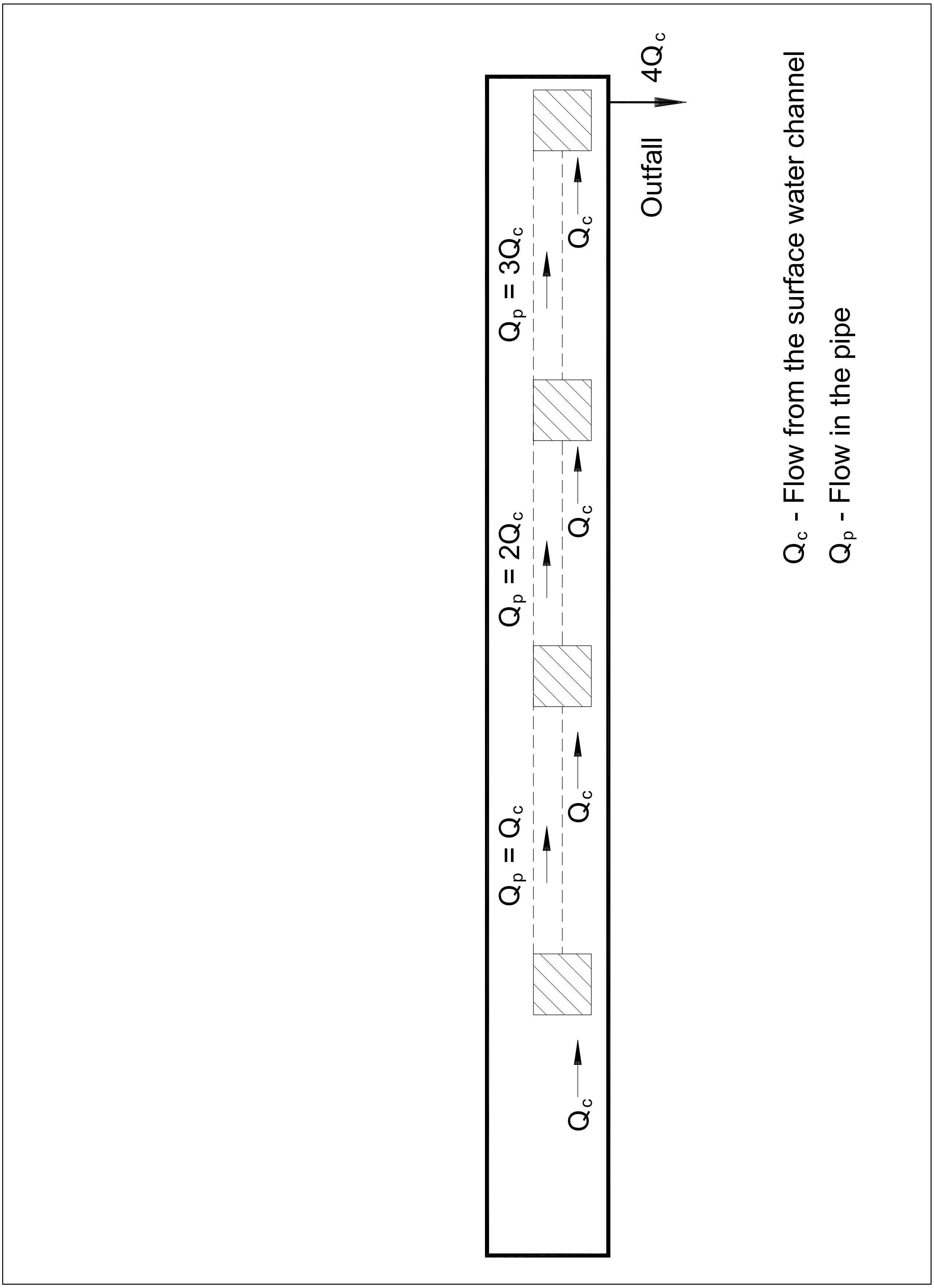

Figure 3 **Longitudinal plan of combined channel and pipe system - example with four collecting chambers**

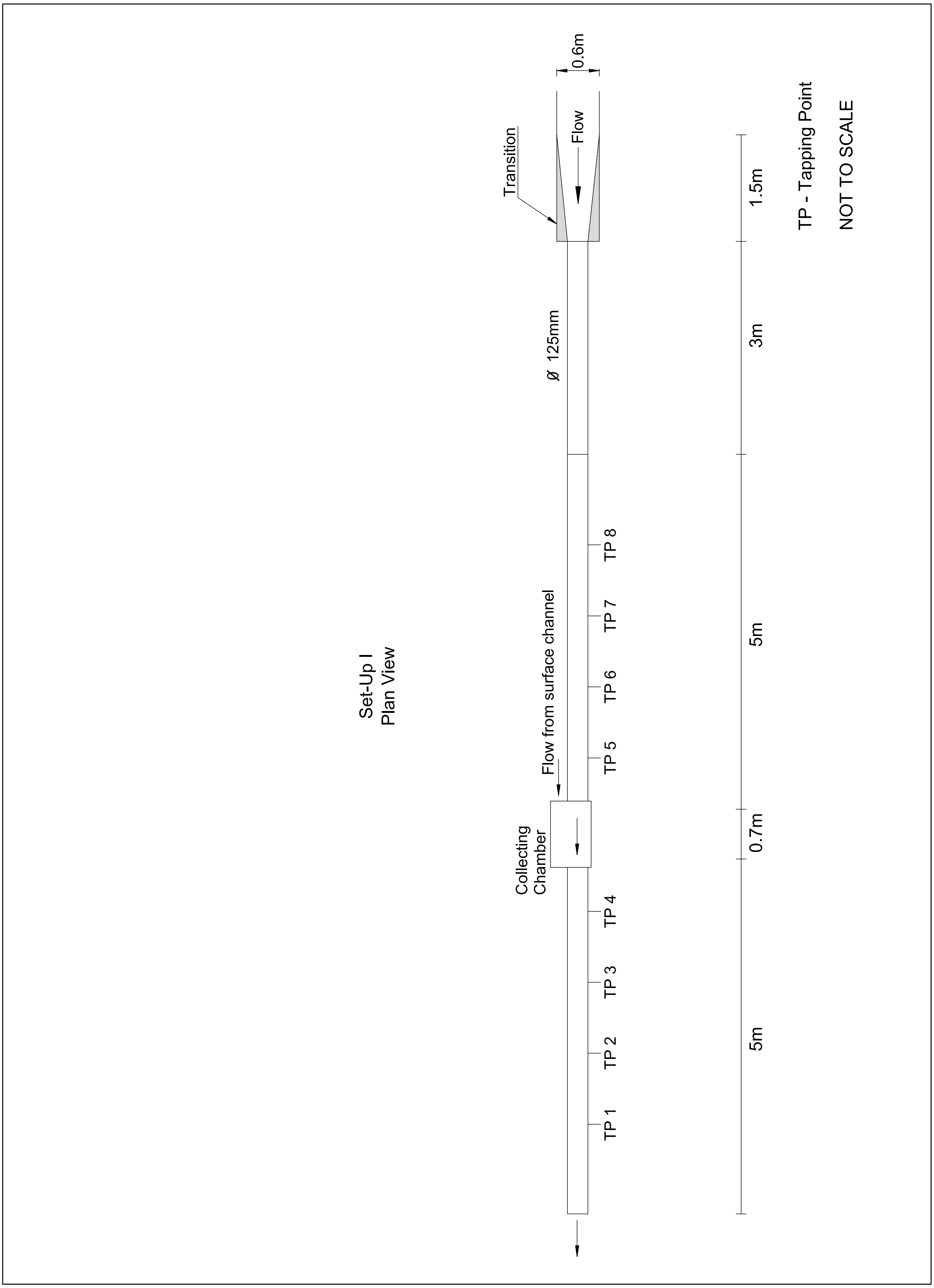

Figure 4 **Set-up 1 - Schematic diagram**

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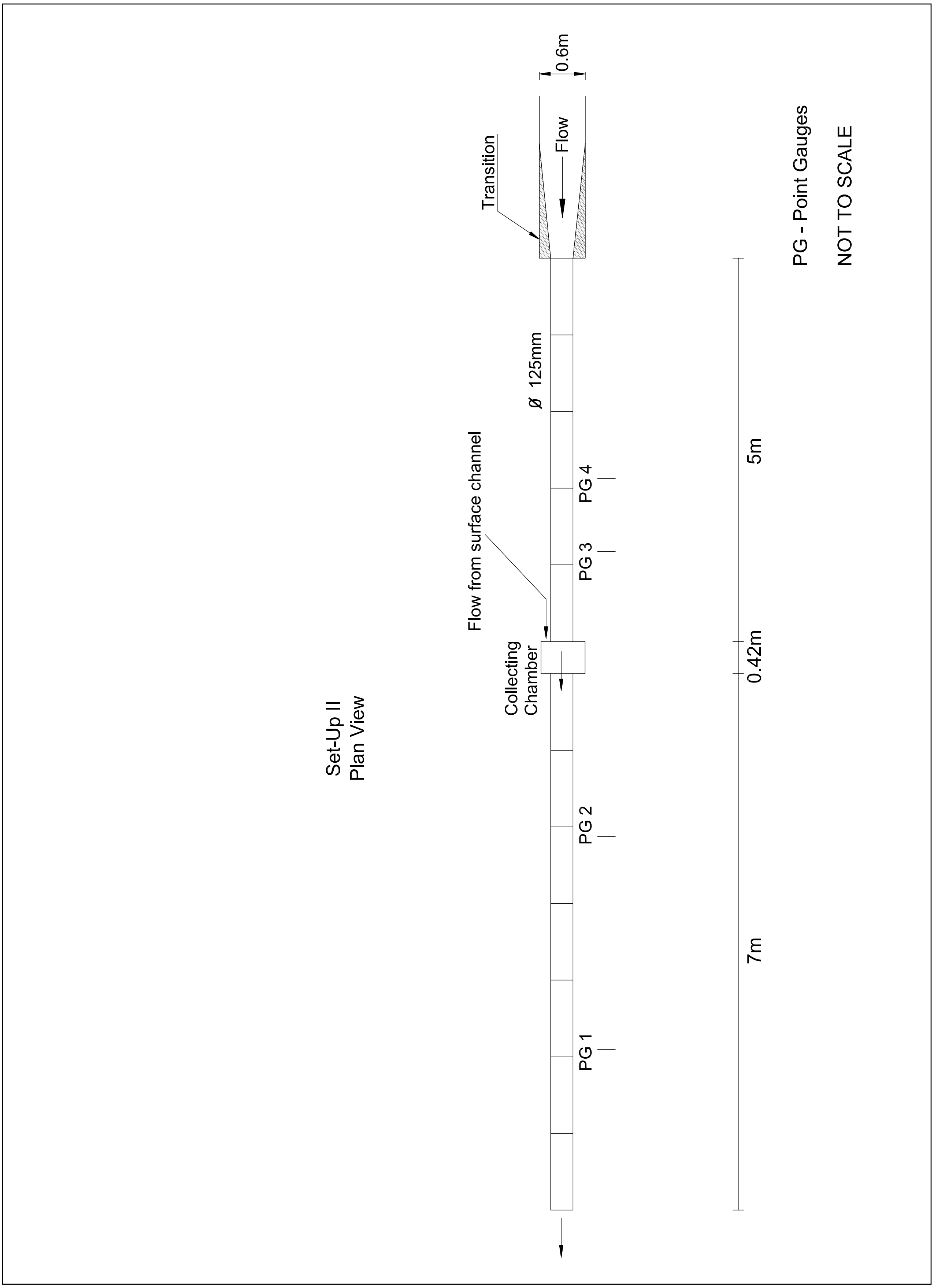

Figure 5 Set-up II – Schematic diagram

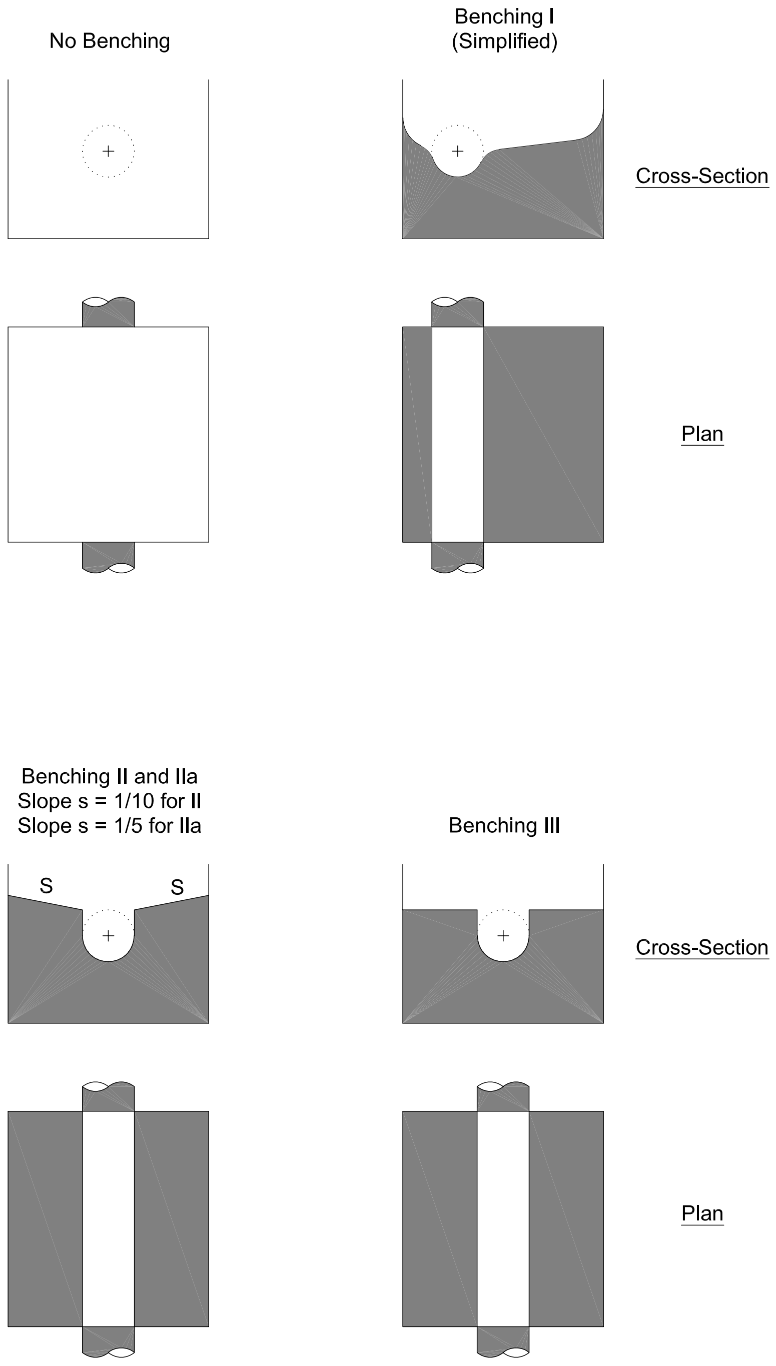

Figure 6 Schematic diagrams of types of benching tested

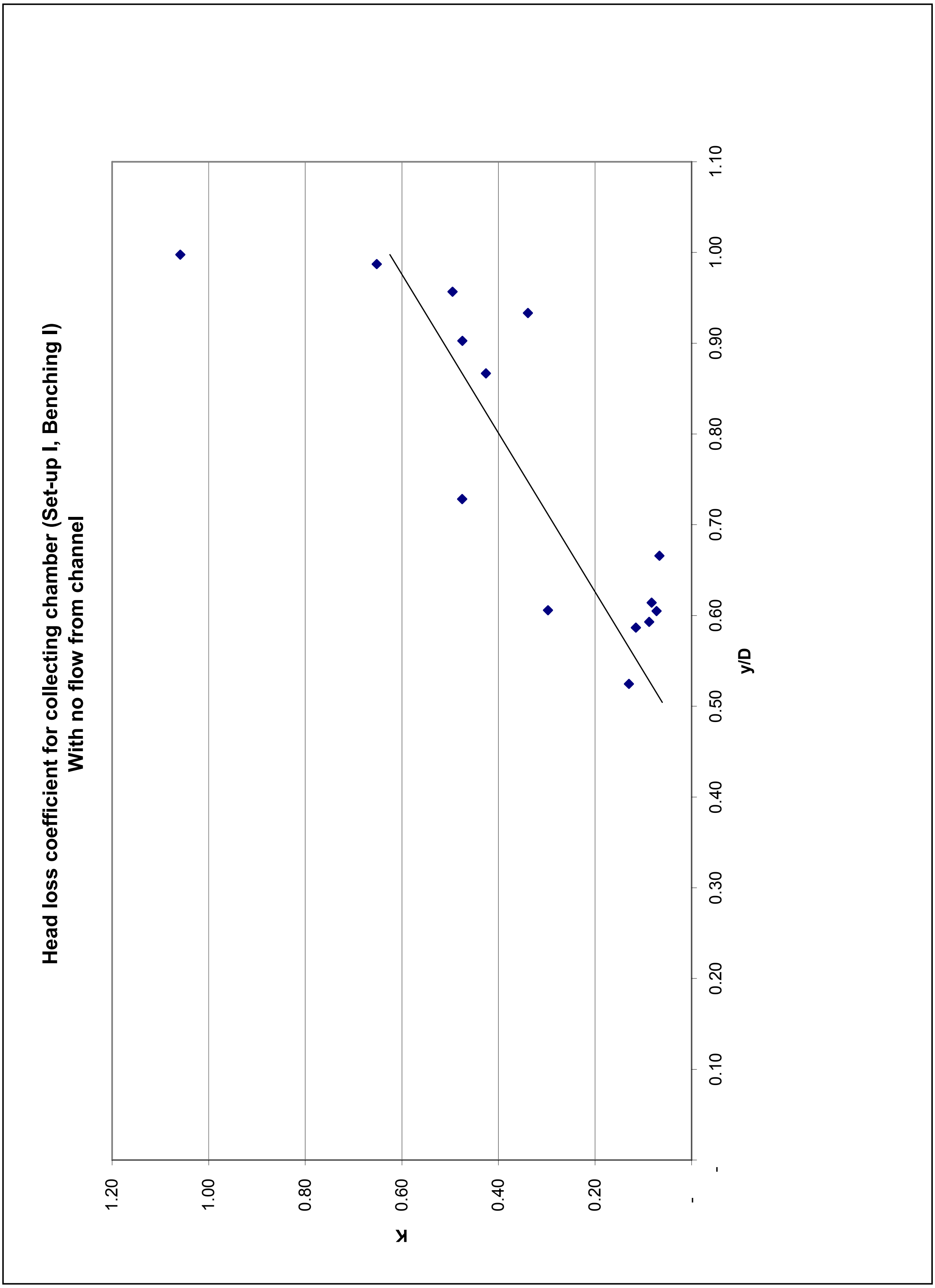

Figure 7 Relationship between K and y/D for tests with no flow from the surface channel

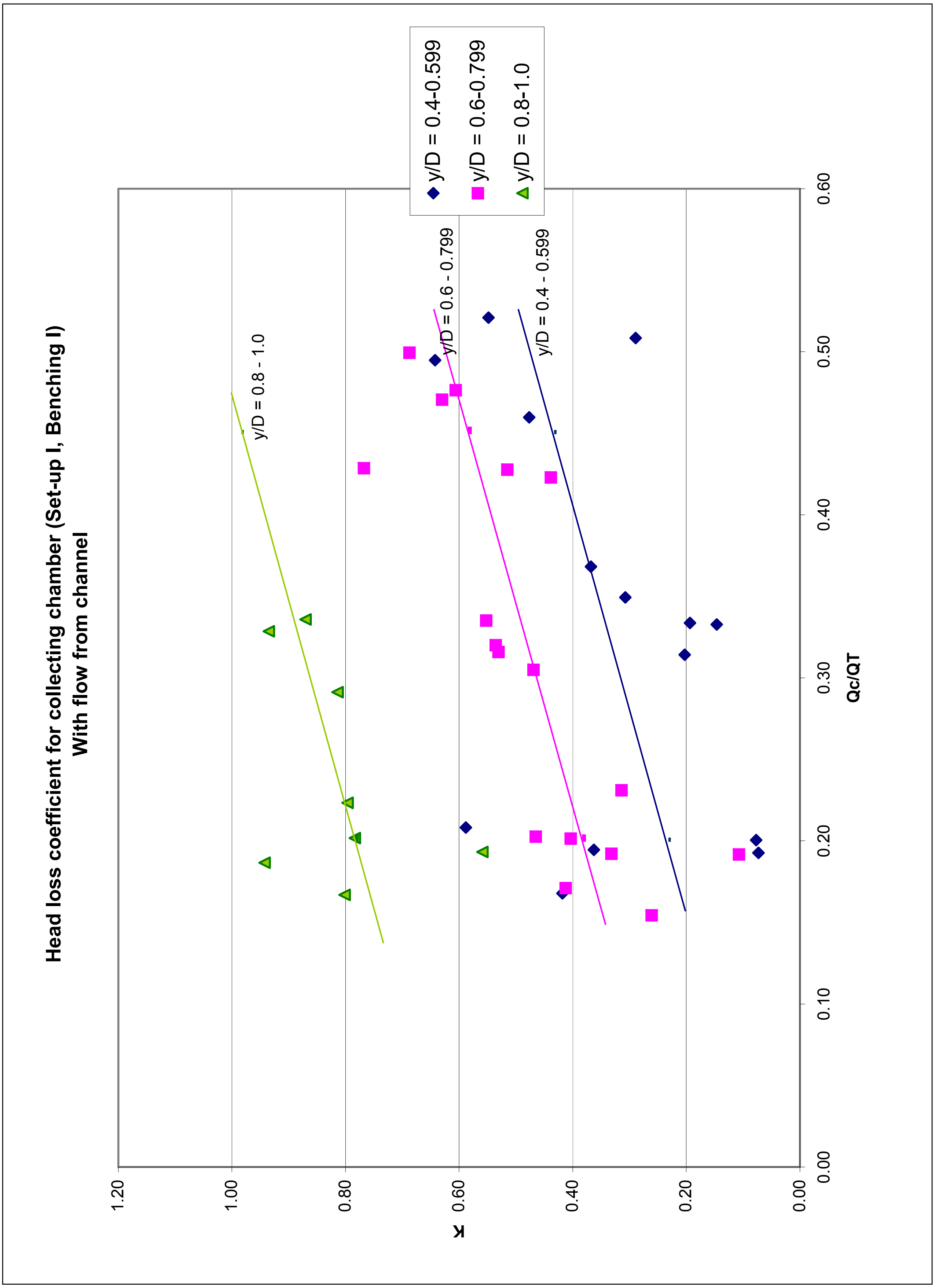

Figure 8 **Relationship between K and Q_c/Q_T for tests with flow from both surface water channel and the pipe**

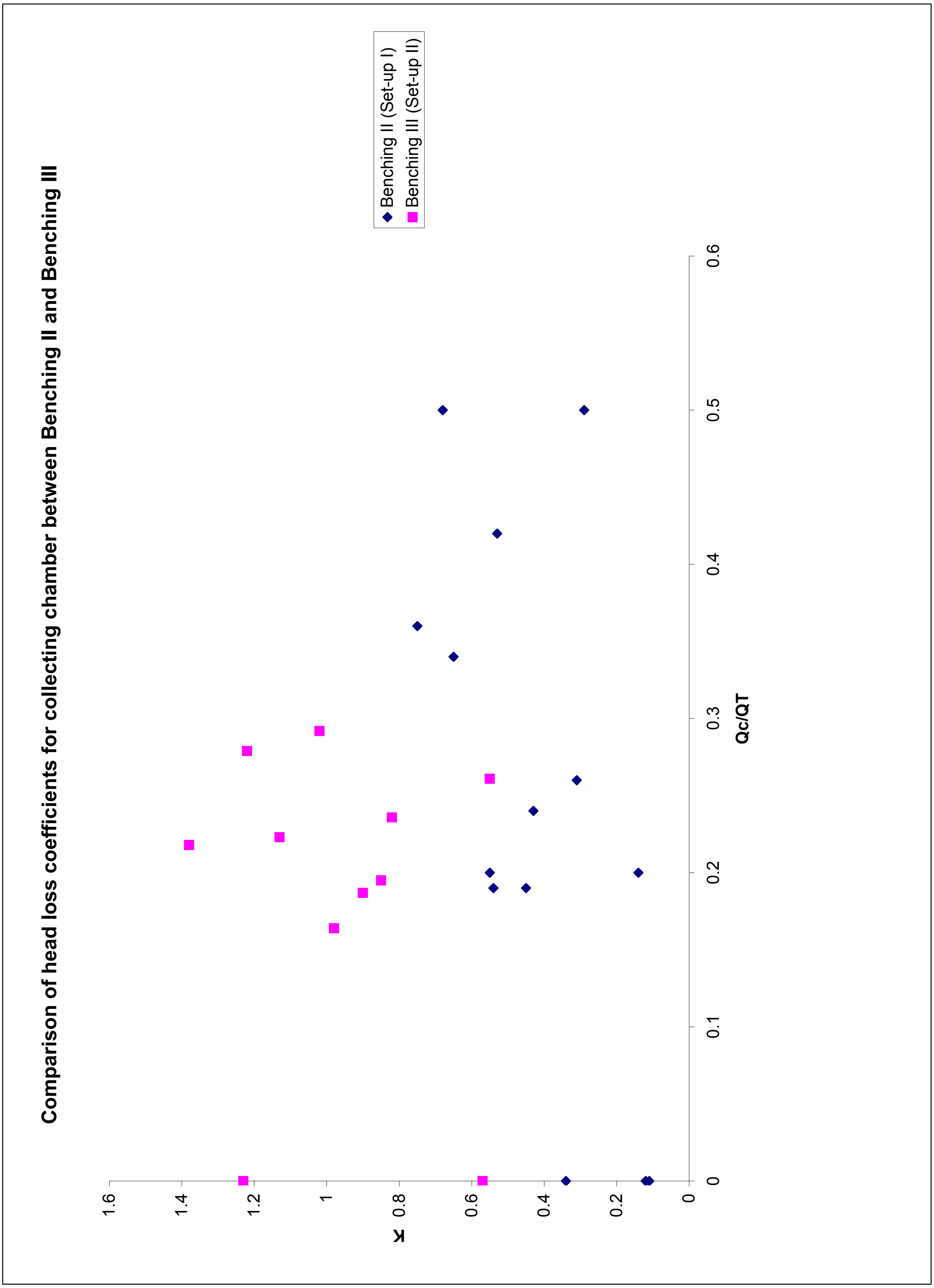

Figure 9 **Comparison of K values between Benchings II and III**

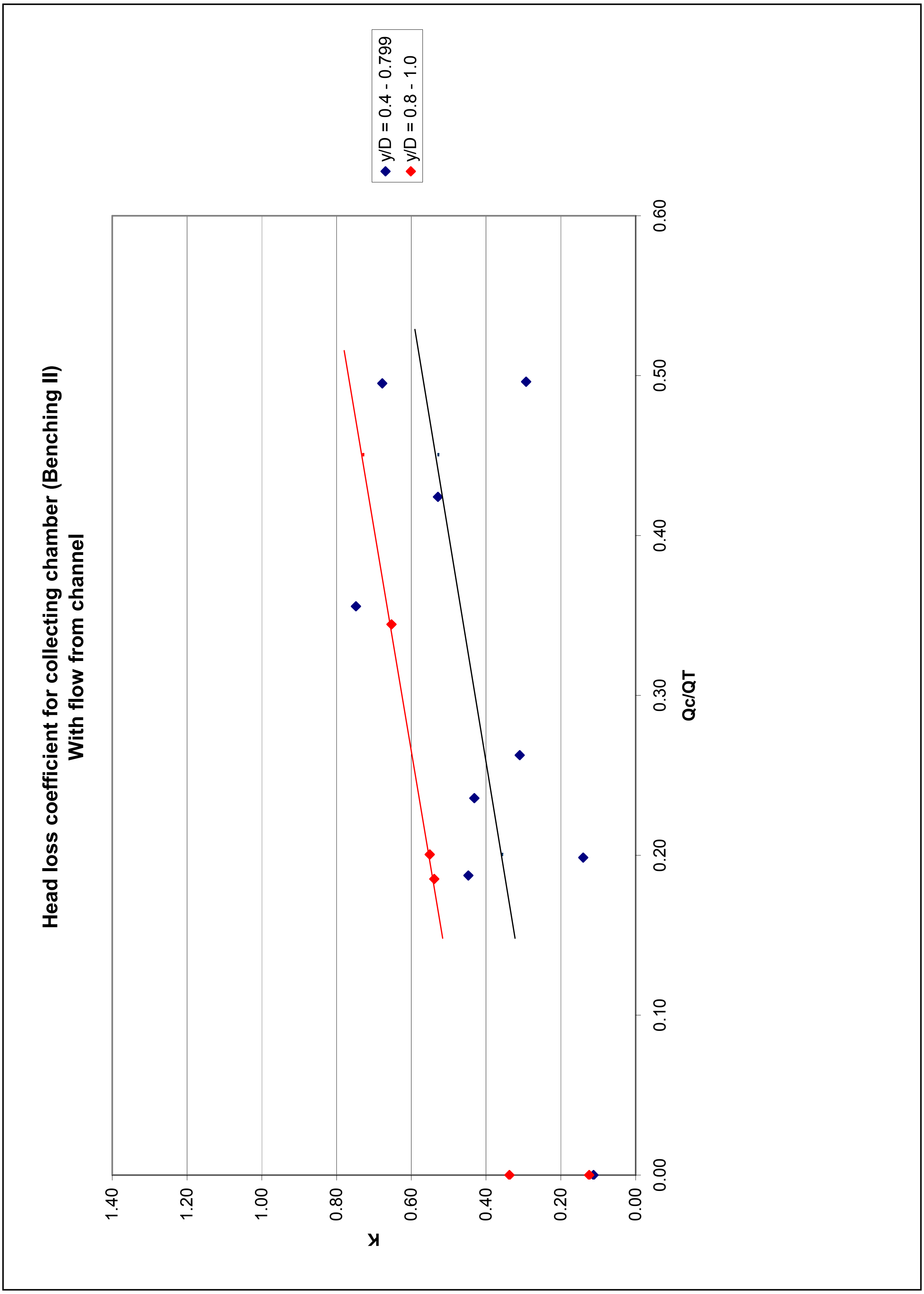

Figure 10 **Relationship between K and Q_c/Q_T for Benching II**

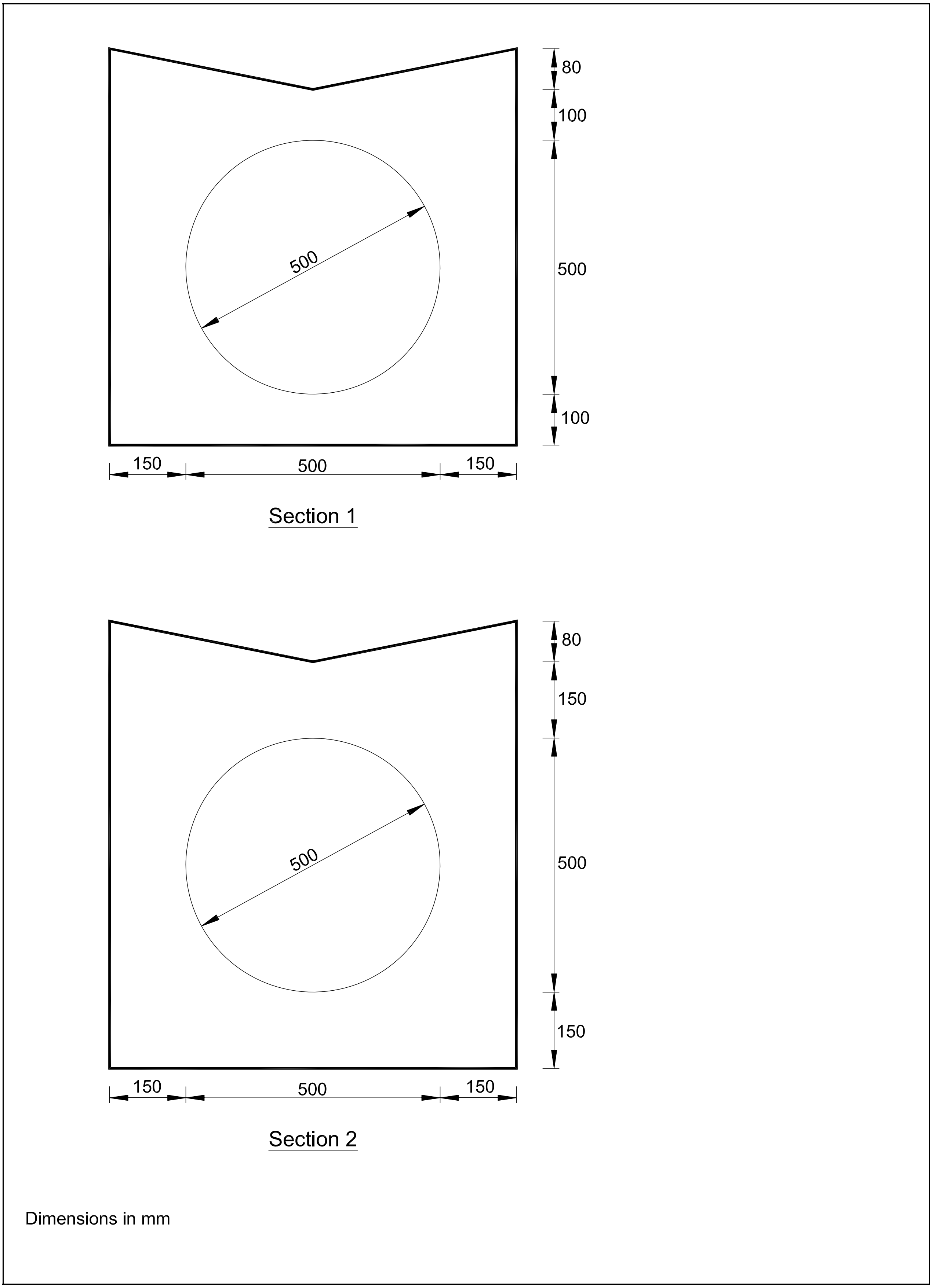

Figure 11 Schematic cross-sections of channel/pipe blocks manufactured at TRL for structural testing

Plates

Plate 1 Set-up I – General view of test section

Plate 2 Set-up I – Upstream transition into test pipe

Plate 3 Set-up II – View from upstream

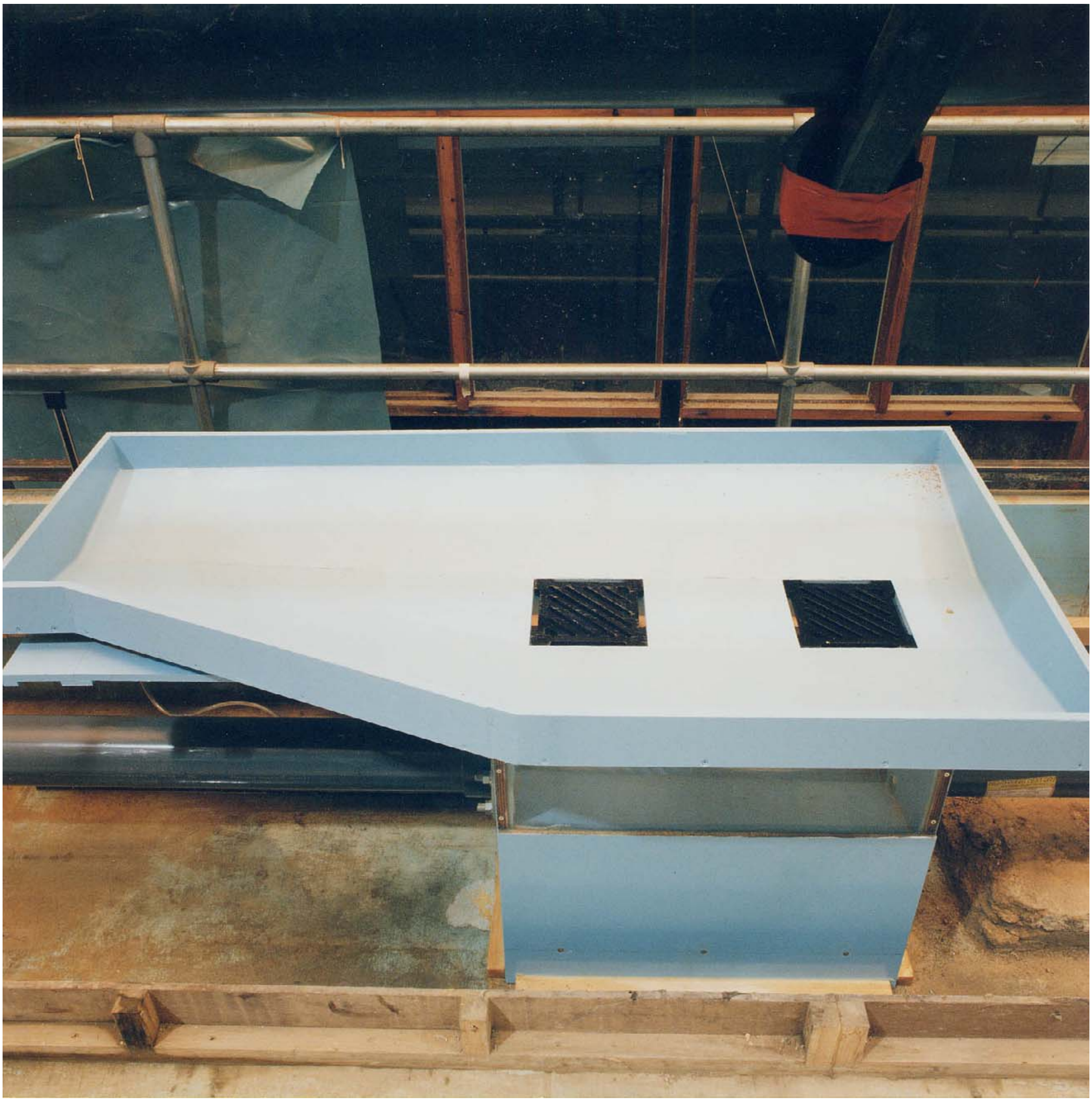

Plate 4 Set-up I – Outfall from surface water channel (off-line)

Plate 5 Set-up II – Outfall from surface water channel (in-line)

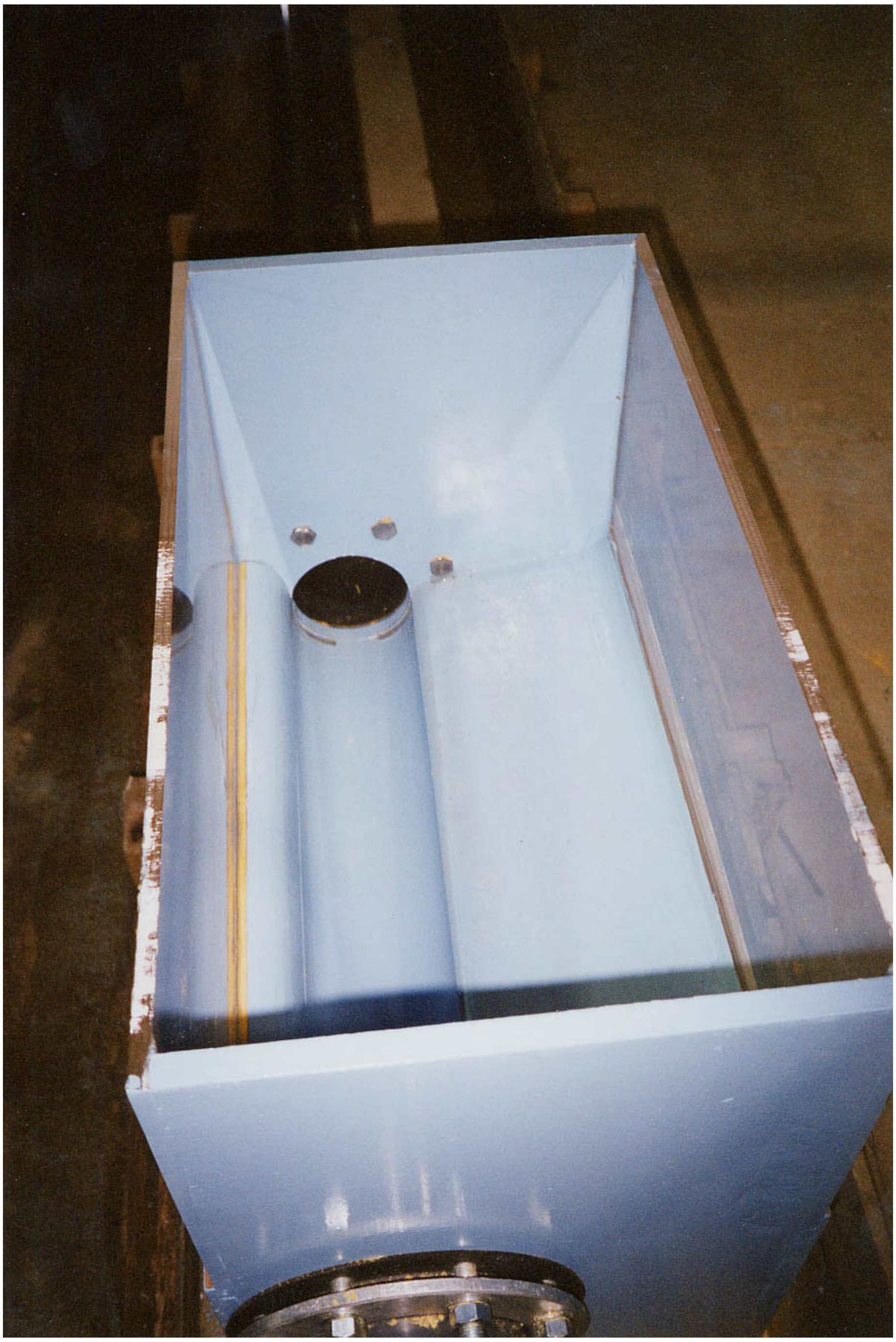

Plate 6 Set-up I – Benching I

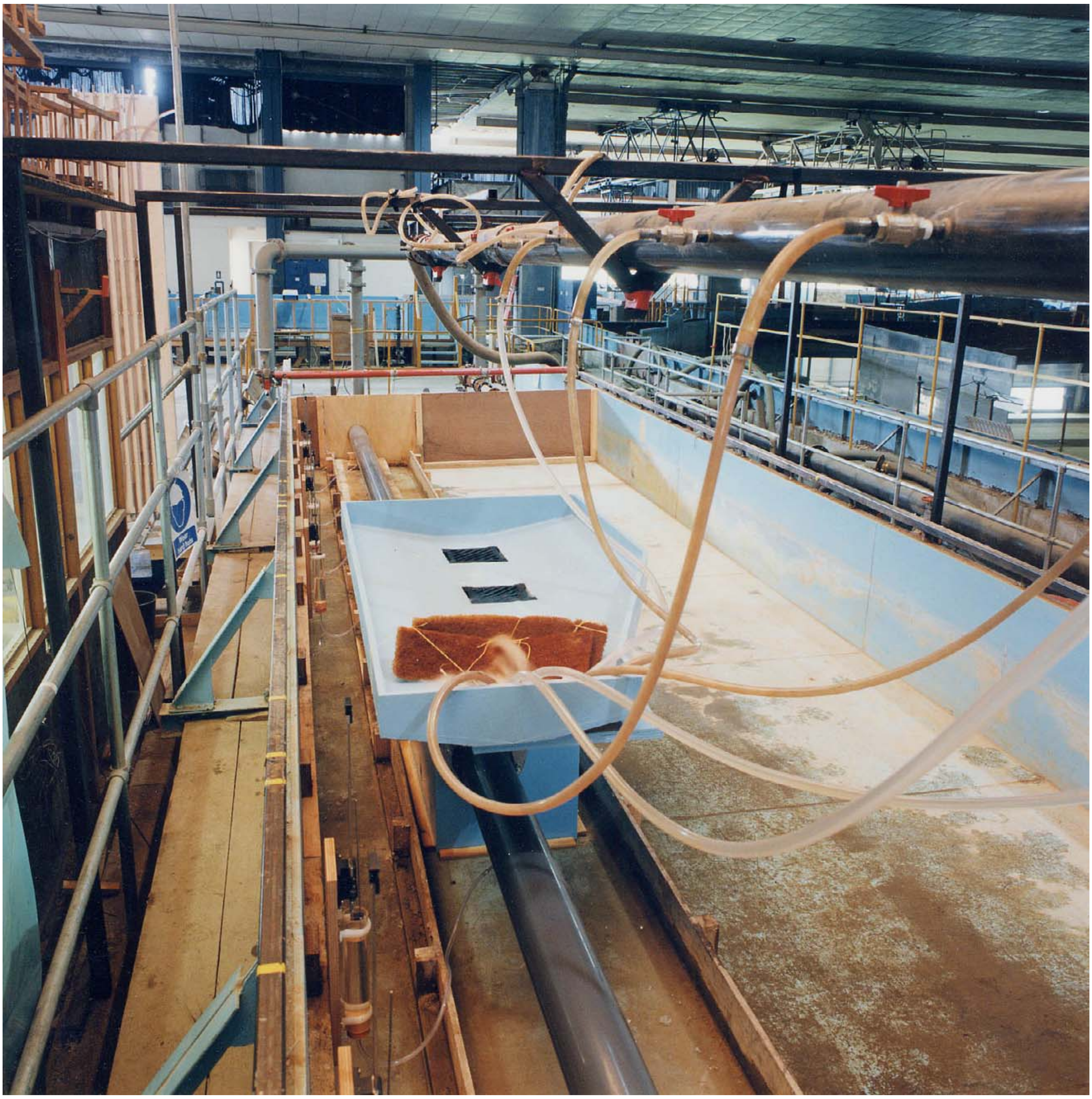

Plate 7 Set-up I (Benching I). General view during test IBI21

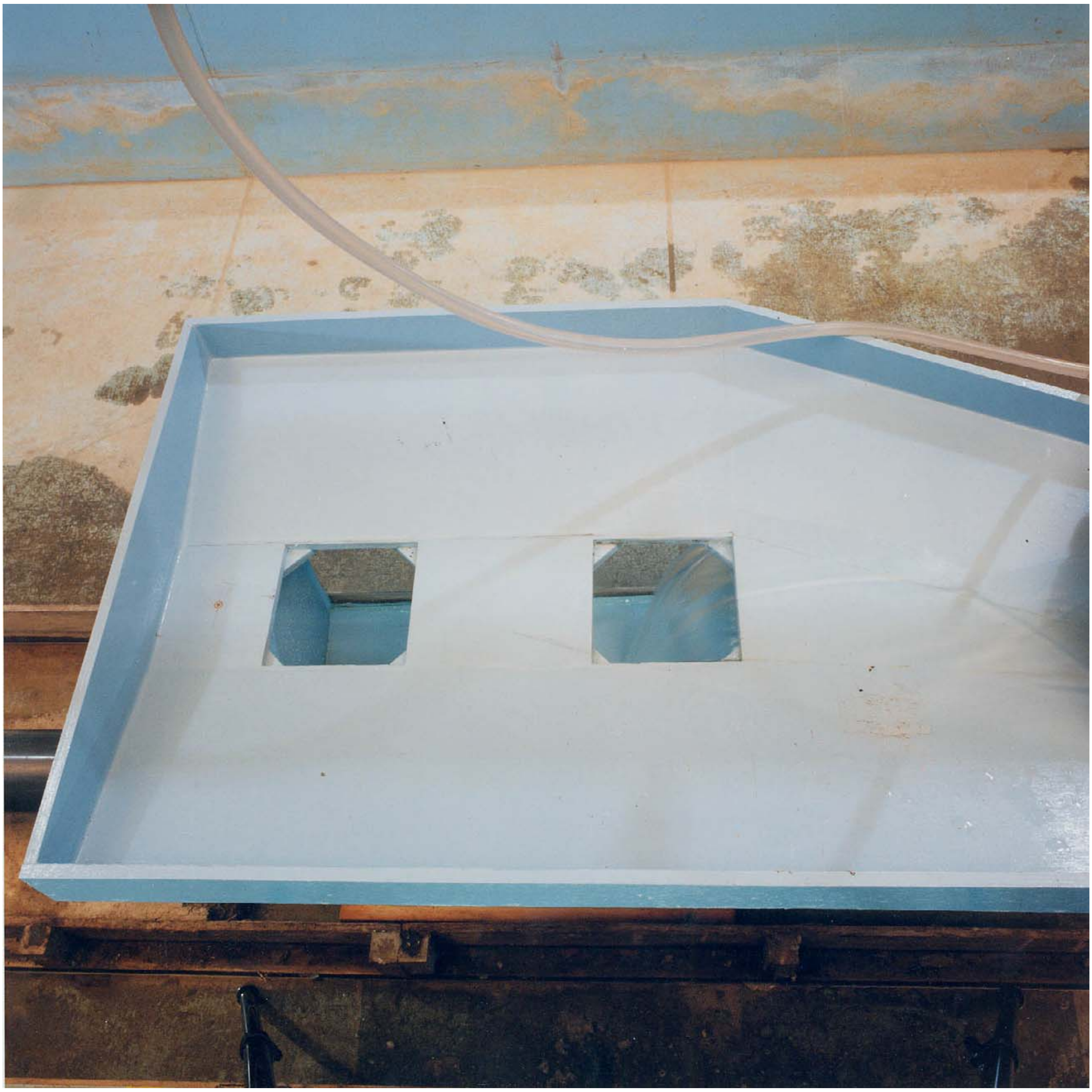

Plate 8 Set-up I (Benching I). Flow from the surface channel entering the chamber with gratings removed for visual observation

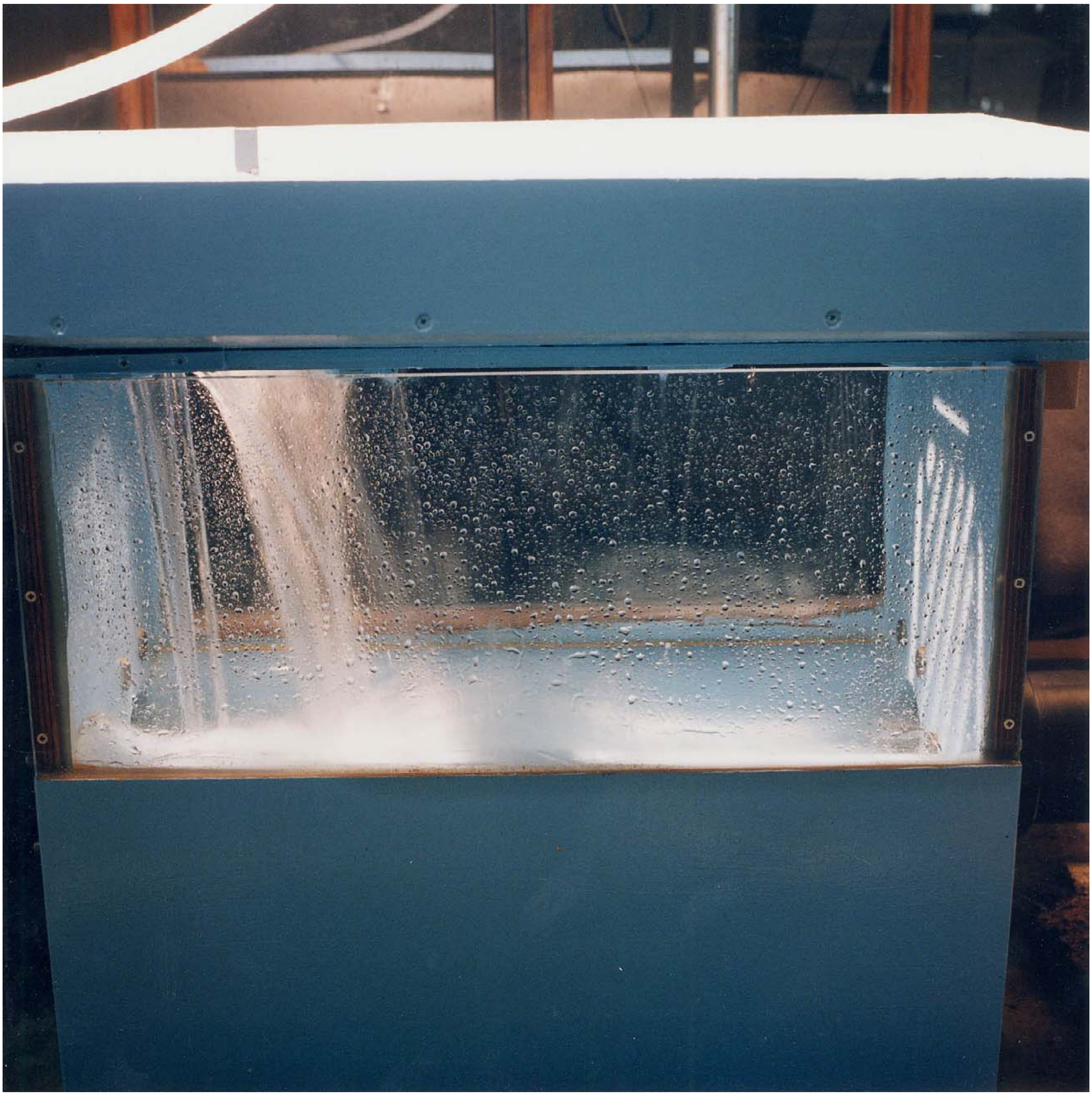

Plate 9 Set-up I (Benching I). Side view of flow inside collecting chamber

Plate 10 Set-up II (Benching IIa). Flow from surface channel entering the chamber with gratings removed for visual observation

Plate 11 Set-up II (Benching IIa). Side view of flow inside collecting chamber

Plate 12 Structural test of Stoney Clouds Section 1: 195mm diameter void

Plate 13 Collapse of Stoney Clouds Section 1: 195mm diameter void

Plate 14 Structural test of Stoney Clouds Section 1: 210mm diameter void

Plate 15 Collapse of Stoney Clouds Section 2: 210mm diameter void

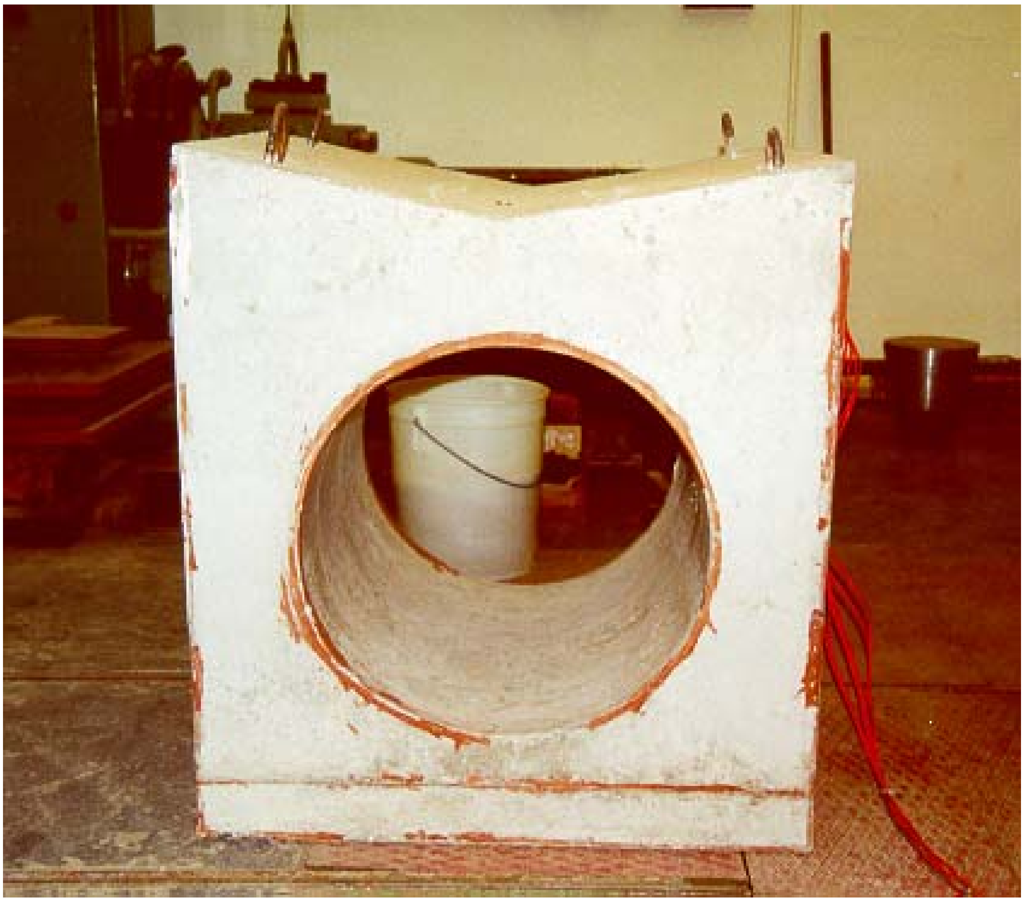

Plate 16 Structural test of TRL Sample 2; 500mm diameter void and 150mm top cover

Plate 17   Collapse of TRL Sample 2; 500mm diameter void and 150mm top cover

Appendix

Strain gauge data from structural test of Sample 2

Appendix - Strain gauge data from structural test of Sample 2

RUN
15:00:54
24-01
S T 1
15:00:55
.0

	1	2	3	4	5	6	load cell		
15:00:55	0.4	0.4	-0.1	0.3	0.2	-0.1	0.000005	0	0
15:01:05	0	0.2	-0.5	-0.2	-0.1	-0.5	0.000007	0.000001	0.0000
15:01:15	0.5	0.3	-0.8	-0.1	-0.2	-0.2	0.000008	0.000002	0.0144
15:01:25	-0.2	0.2	-0.5	0	-0.2	-0.8	0.000007	0.000001	0.0184
15:01:35	0	0.1	-0.8	-0.1	-0.5	-0.6	0.000008	0.000002	0.0120
15:01:45	0	0.6	-1.2	-0.2	-0.7	-0.4	0.000007	0.000002	0.0192
15:01:55	-0.2	0.3	-0.2	0.1	-0.5	-0.2	0.000008	0.000003	0.0176
15:02:05	-0.2	0.2	-1	-0.1	-0.7	-0.8	0.000008	0.000002	0.0248
15:02:15	-0.2	0	-1.2	0	-0.6	-0.7	0.000007	0.000001	0.0216
15:02:25	0.1	0	-0.8	-0.3	-0.6	-1	0.000008	0.000002	0.0136
15:02:35	0.1	-0.1	-1.1	-0.2	-0.3	-0.9	0.000025	0.000019	0.0208
15:02:45	0	0	-1.1	-0.3	-0.2	-0.7	0.000032	0.000026	0.1552
15:02:55	0.2	0.3	-0.6	141.1	-0.5	-0.4	0.000032	0.000027	0.2112
15:03:05	0.2	0	-1	-0.2	-0.6	-0.3	0.000032	0.000026	0.2168
15:03:15	0.4	-0.2	-0.8	0	-0.1	-0.8	0.000032	0.000027	0.2152
15:03:25	0.1	-0.1	-0.4	0	-0.4	-0.3	0.000033	0.000027	0.2176
15:03:35	0	-0.2	-1.5	-0.5	-1.1	-0.9	0.000033	0.000027	0.2208
15:03:45	0.2	-0.1	-1	-0.3	-0.3	-0.7	0.000033	0.000027	0.2184
15:03:55	-0.2	0	-0.5	-0.3	-0.2	-0.5	0.000032	0.000026	0.2224
15:04:05	-0.3	-0.5	-1.1	-0.5	-0.6	-0.5	0.000047	0.000041	0.2136
15:04:15	2.3	-2.9	0.2	-1.7	0	-2.8	0.000602	0.000596	0.3320
15:04:25	10.2	-9.4	3.8	-5.6	2.2	-8.9	0.002276	0.002271	4.7712
15:04:35	26	-19.3	12.3	-8.8	4.8	-12.6	0.004313	0.004307	18.1680
15:04:45	37.1	-23.8	16.7	-10.6	6.7	-15.7	0.005092	0.005087	34.4624
15:04:55	36	-22.7	16	-9.8	6.3	-15	0.004792	0.004786	40.6968
15:05:05	35.6	-22.4	16.2	-9.9	6.3	-14.8	0.004718	0.004713	38.2920
15:05:15	35.9	-22.2	16.1	-9.6	6.6	-14.3	0.004684	0.004678	37.7040
15:05:25	38.3	-23.5	17.8	-10.5	6.6	-15.2	0.005102	0.005096	37.4280
15:05:35	41.4	-25.3	18.6	-11.1	7.2	-16.4	0.005337	0.005331	40.7744
15:05:45	45.5	-26.1	20.1	-11.1	7.7	-17.1	0.005641	0.005635	42.6528
15:05:55	49.6	-27.4	21.5	-11.4	8.2	-17.7	0.005897	0.005891	45.0872
15:06:05	53.9	-28.9	23.3	-12	9	-19.4	0.006212	0.006207	47.1312
15:06:15	64.4	-31.4	26.2	-13.1	10	-20.5	0.006677	0.006671	49.6568
15:06:25	76.2	-34.3	29.7	-13.5	11.1	-22.3	0.007283	0.007277	53.3712
15:06:35	90.5	-38	34.7	-15	13.4	-24.6	0.007943	0.007937	58.2208
15:06:45	113.3	-43	44.3	-16.5	15.5	-27.5	0.008645	0.008640	63.5000
15:06:55	141.5	-48.3	61.3	-17.2	20.3	-30.5	0.009376	0.009370	69.1216
15:07:05	184.6	-54.6	81.1	-17.4	27.3	-32.7	0.010143	0.010138	74.9624
15:07:15	250.3	-61.8	111.8	-16.7	37.5	-33.6	0.010922	0.010917	81.1048
15:07:25	415.8	-73	134	-5.8	60.7	-22.4	0.011582	0.011577	87.3368
15:07:35	821.2	-93.8	262.9	142.1	188.9	64.3	0.011700	0.011695	92.6168
15:07:45	0	24.7	211.9	0	304.6	154.7	0.001222	0.001216	93.5600
15:07:55	0	25	206.8	0	300	145.1	0.001032	0.001026	9.7328
15:08:05	0	24.9	204	0	295.4	140.4	0.000968	0.000963	8.2104
15:08:15	0	24.9	202.1	0	293	137.5	0.000924	0.000918	7.7056
15:08:25	0	24.7	201.2	0	290.4	134.3	0.000855	0.000849	7.3496
15:08:35	0	23.7	201.1	0	288.4	132.3	0.00083	0.000824	6.7960
15:08:45	0	22.8	201.1	0	286.7	131.5	0.000683	0.000677	6.5944
15:08:55	0	22.3	201.1	0	283.5	130	0.000556	0.000550	5.4232
15:09:05	0	21.9	201.1	0	281.2	129.5	0.000632	0.000626	4.4024

15:09:15	0	21.6	200.6	0	281.1	128.9	0.000914	0.000908	5.0136
15:09:25	0	22	200.9	0	281.2	128	0.001344	0.001338	7.2704
15:09:35	0	23.6	201.6	0	283	127.6	0.001077	0.001072	10.7088
15:09:45	0	24	202.6	0	283.9	127.9	0.001901	0.001896	8.5776
15:09:55	0	21.8	203.4	0	283.6	127.5	0.002036	0.002030	15.1680
15:10:05	0	21.6	203.8	0	283.9	127.2	0.001892	0.001886	16.2464
15:10:15	0	0	204.2	0	0	127.4	0.001635	0.001629	15.0912
15:10:25	0	0	204.6	0	0	127.3	0.001643	0.001637	13.0384
15:10:35	0	0	205.3	0	0	127.4	0.001693	0.001687	13.1016
15:10:45	0	0	205.5	0	0	127.3	0.001586	0.001580	13.5008
15:10:55	0	0	205.2	0	0	127.6	0.001584	0.001579	12.6440
15:11:05	0	0	205.9	0	0	127.8	0.001280	0.001274	12.6336
15:11:15	0	0	206.4	0	0	127.6	0.001233	0.001227	10.1976
15:11:25	0	0	206.6	0	0	127.9	0.001047	0.001041	9.8192
15:11:35	0	0	207.3	0	0	127.6	0.000971	0.000965	8.3312
15:11:45	0	0	207.9	0	0	127.7	0.000822	0.000816	7.7264
15:11:55	0	0	209	0	0	128.3	0.000751	0.000746	6.5304
15:12:05	0	0	209.3	0	0	127.9	0.000658	0.000652	5.9680
15:12:15	0	0	209.9	0	0	128.1	0.000414	0.000408	5.2200
15:12:25	0	0	210.3	0	0	127.8	0.000348	0.000343	3.2664
15:12:35	0	0	210.7	0	0	127.6	0.000274	0.000268	2.7440
15:13:05	0	0	213.4	0	0	128.2	0.000153	0.000147	2.1496
15:13:15	0	0	214.8	0	0	128.9	0.000046	0.000041	1.1792
15:13:35	0	0	218	0	0	129.7	0.000115	0.000109	0.3288
15:13:45	0	0	220.2	0	0	131.1	0.000042	0.000036	0.8792
15:13:55	0	0	0	0	0	0	0.000001	-0.000004	0.2952
15:14:05	0	0	0	0	0	0	0.000001	-0.000004	-0.0352
15:14:15	0	0	0	0	0	0	0.000001	-0.000003	-0.0320
15:14:25	0	0	0	0	0	0	0.000001	-0.000004	-0.0312
15:14:35	0	0	0	0	0	0	0.000001	-0.000004	-0.0368
15:14:45	0	0	0	0	0	0	0.000001	-0.000004	-0.0352
15:14:55	0	0	0	0	0	0	0.000001	-0.000004	-0.0328
15:15:05	0	0	0	0	0	0	0.000002	-0.000003	-0.0320
15:15:15	0	0	0	0	0	0	0.000003	-0.000002	-0.0240
15:15:25	0	0	0	0	0	0	0.000003	-0.000002	-0.0208
15:15:35	0	0	0	0	0	0	0.000003	-0.000002	-0.0184
15:15:45	0	0	0	0	0	0	0.000003	-0.000002	-0.0200
15:15:55	0	0	0	0	0	0	0.000003	-0.000002	-0.0160
15:16:05	0	0	0	0	0	0	0.000004	-0.000001	-0.0200
15:16:15	0	0	0	0	0	0	0.000005	-0.000000	-0.0112
15:16:25	0	0	0	0	0	0	0.000004	-0.000001	-0.0024
15:16:35	0	0	0	0	0	0	0.000004	-0.000001	-0.0120
15:16:45									