NWRI CONTRIBUTION 85-15

Marsalek (73)

HEAD LOSSES AT SELECTED SEWER MANHOLES

by

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FOREWORD

The APWA Research Foundation with the support of 32 public agencies and the Hydraulics Division of the National Water Research Institute have jointly undertaken a study to improve the design of junction manholes. Hydraulic head loss in sanitary and stormwater systems can lead to diminished capacity of the downstream pipes. Such capacity loss may result in raising the hydraulic grade line and the creation of flooding conditions. Relief facilities are often required or new development prohibited in order to protect adjoining property. Thus, minimization of hydraulic head loss in both new and existing systems may be an important tool in alleviation of problems in some key facilities.

Additional reports will be published concerning other manhole configurations as the research is completed.

The American Public Works Association wishes to thank the National Water Research Institute for its assistance and the facilities made available for the study.

Richard H. Sullivan
General Manager
APWA Research Foundation

AVANT-PROPOS

Le Fondation de recherche de l'APWA a entrepris, avec l'aide de 32 organismes publics et de la Division de l'hydraulique de l'Institut national de recherche sur les eaux une étude conjointe sur la conception des regards de raccordement. Les pertes de charge hydraulique dans les réseaux d'égouts séparatifs et pluviaux peuvent réduire la capacité de débit des tuyaux situés en aval. Cette perte de capacité de débit peut provoquer l'élévation de la ligne piézométrique et provoquer des inondations. Il est souvent nécessaire de construire des installations de décharge ou d'interdire les nouvelles constructions afin de protéger les propriétés adjacentes. Par conséquent, la réduction des pertes de charge dans les installations tant nouvelles qu'existantes peut être un bon moyen d'éliminer de tels problèmes dans certaines installations de première importance.

On produira des rapports supplémentaires sur d'autres modèles de regards lorsque les recherches seront terminées.

L'American Public Works Association désire remercier l'Institut national de recherche sur les eaux de son aide et des installations qu'il a mises à sa disposition au cours de l'étude.

Le directeur général de la Fondation de recherche de l'APWA,

Richard H. Sullivan

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ABSTRACT

Pressure and head losses have been studied for three types of sewer junctions - junctions with a 90° bend, junctions of a main with a perpendicular lateral, and junctions of two opposed laterals. For the pressurized flow, head losses depended on the junction geometry and, in the case of junctions with more than two pipes, on the relative lateral inflow. Among the geometrical parameters, the junction benching and relative pipe sizes were particularly important. Full benchings reaching to the pipe crown performed the best by reducing the junction head losses and releases of sulphide gases. At junctions of a main with a perpendicular lateral, the losses in the main increased with an increasing lateral discharge (for a constant lateral diameter) or an increasing lateral flow velocity (for a constant discharge). For junctions of two opposed laterals, the lowest losses were observed at junctions with full benching, equal lateral inflows, and equal lateral diameters. Limited experiments in the open-channel flow region showed that junction losses for such conditions were rather small. Such losses were again mostly affected by the benching design and the relative lateral inflow.

RÉSUMÉ

On a étudié les pertes de charge et de pression dans trois modèles de raccordements d'égouts; les raccordements coudés (90°), le raccordement d'une conduite principale avec une conduite latérale perpendiculaire et le raccordement de deux conduites latérales opposées. Dans le cas de l'écoulement sous pression, les pertes de charge dépendaient de la configuration géométrique du raccordement et, dans le cas du raccordement de plus de deux conduites, du débit entrant latéral relatif. Parmi les paramètres géométriques, la configuration des banquettes de raccordement et la taille relative des conduites étaient particulièrement importants. Les banquettes pleine hauteur - qui atteignent la voûte de la conduite - ont donné les meilleurs résultats en réduisant les pertes de charge au point de raccordement et l'émission de gaz sulfureux. Dans le cas du raccordement d'une conduite principale avec une conduite latérale perpendiculaire, les pertes de charge augmentaient en fonction de l'accroissement du débit latéral (pour un diamètre constant) et de l'augmentation de la vitesse d'écoulement latéral (pour un débit constant). Dans le cas du raccordement de deux conduites latérales opposées, on a constaté les pertes les plus faibles lorsqu'il y avait des banquettes pleine hauteur, des débits entrants latéraux équivalents et des diamètres latéraux équivalents. Des expériences limitées effectuées dans la zone d'écoulement à surface libre indiquent que les pertes au point de raccordement dans de telles conditions étaient plutôt faibles. Ces pertes variaient elles aussi selon la configuration des banquettes et la débit entrant latéral relatif.

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1.0 INTRODUCTION

The hydraulic design of sewer networks is based on the equations of mass continuity and energy conservation. The latter equation requires consideration of two types of head losses - skin friction losses in sewer pipes and minor losses at various appurtenances and special structures, among which the most common are sewer pipe junction manholes. Junction manholes are typically used where two or more pipes join together, or where the pipe diameter, grade or alignment change.

While the friction losses have been extensively studied in the past and can be adequately characterized for practical purposes, only limited information is available on energy losses at sewer pipe junctions. Yet the losses at junctions may often exceed the friction losses and seriously limit the sewer system capacity. Consequently, the sewer system may become surcharged and such conditions often lead to basement flooding or sewage overflows. A direct link between the junction losses and increased incidence of combined sewer overflows was reported by the City of Scarborough.

Although the junction head losses as well as other minor losses need to be considered in the sewer design regardless of the design approach taken, the importance of such considerations has increased in recent years with the introduction of sophisticated computerized design methods. In the traditional sewer design based on hand calculations, sewer systems are designed as open-channel networks in which the minor losses are not excessive and the hydraulic grade line does not exceed the pipe crown elevation. Under such circumstances even crude approximations of junction head losses may be adequate.

Recent design experience shows that significant savings can be achieved by allowing storm sewers to surcharge, to a limited extent, before any damages occur. Such a design is based on a computerized pressure flow routing through the sewer network and on the calculation of the hydraulic grade line, which is maintained below the critical elevation to avoid flood damages. The accuracy and sophistication of such calculations is defeated by an improper consideration, or neglect, of juction energy losses which can become fairly large in a surcharged system.

Recognizing the importance of junction energy losses in estimating the capacity and collection efficiency of sewer systems, the American Public Works Association (APWA) and the Hydraulics Division of the National Water Research Institute (NWRI) decided to undertake a joint laboratory study of head losses at various types of sewer junction manholes. The terms of reference of this joint study are presented below.

Head losses at junctions are affected by a large number of parameters. To conserve research funds, it was desirable to limit the study scope by establishing research priorities. For this purpose, the views and design practices of the 32 study sponsors, were surveyed (10). The survey results, relevant to the study execution, are summarized below.

Study Objectives: To establish head losses at selected types of junctions and to study practical means of reducing such losses.

Junctions To Be Studied: Altogether, seven types of junctions (see Fig. 1 - Junction Types Recommended for Investigation) were recommended for laboratory investigations. Because of budget limitations, only the first three junctions could be investigated in this phase of the research.

Other survey findings dealt with sponsors' design practices. It was noted that manholes were designed with both round and square bases. The round bases were used in more than 90% of all cases. About 60% of all sewers designed were 0.457 m (18 in) in diameter or smaller. The vertical arrangement of pipes at junctions was such that pipe crowns were matched at the junction, or the grade was maintained through the junction. It further followed from the survey that junctions should be tested for pressurized flow and the head losses should be expressed in terms of the outlet velocity head and the junction geometry.

The arrangements for the study conduct were outlined in the Foreword. In particular, the study was conducted by the staff of NWRI and APWA under the direction of the Steering Committee. The overall direction for the study was provided by the Project Advisory Committee. The financial support for the project was provided by the study sponsors, APWA and NWRI. Special thanks are due to all sponsors, advisors, consultants, and their organizations for making this project possible.

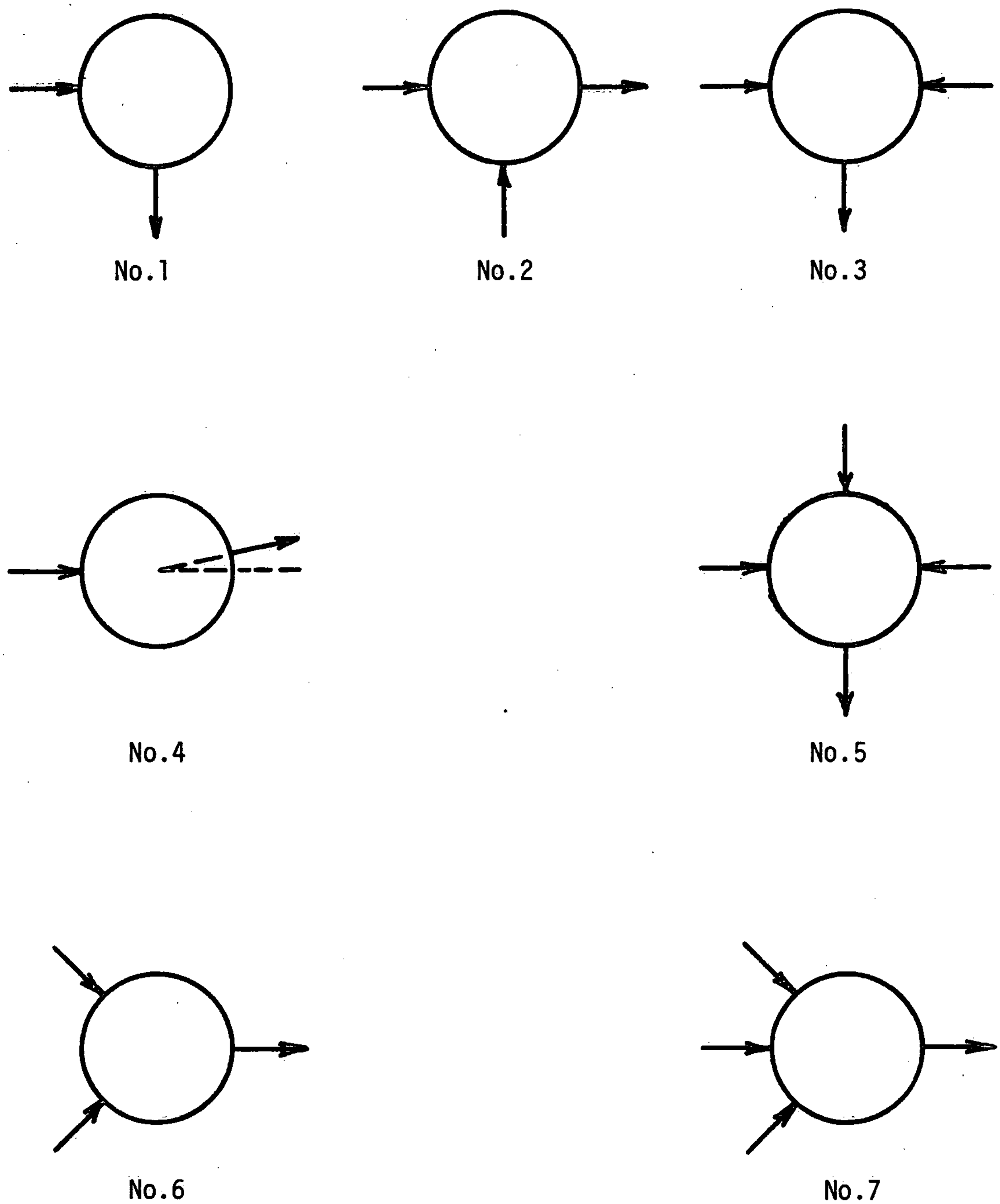


Fig.1. Junction Types Recommended for Investigation

2.0 GENERAL CONSIDERATION

General problems of the flow through junctions have been discussed by Chow (4) who concluded that the flow through junctions was a complicated problem whose generalization by analytical means was not possible and the best solution would be found through a model study of junction flow characteristics. Indeed, an exhaustive literature search indicated that among various approaches, the study of head losses in physical models was the most common. Other approaches included prototype observations and the application of the momentum equation.

Ackers (1) observed head losses at four types of manholes with a single pipe passing through and with or without changes in the pipe alignment. He concluded that in open-channel flow the head losses at the manholes studied were rather small, but increased considerably in pressurized flow, particularly in junctions with a change in the pipe alignment. No other prototype data were found in the literature.

The momentum equation has been applied to the junction problem by several investigators (6,8). Such applications generally follow those for the manifold flow problem and involve simplifying assumptions which require further experimental verification. Whenever appropriate, references to the solutions of the momentum equation are made.

Thus, the studies of junction head losses in scale models represent the most common approach which was also adopted in this study. Model investigations should start with a dimensional analysis and considerations of the model similarity, as presented below.

2.1 Dimensional Analysis

Considering the junction notation sketch in Fig. 2 - Junction Notation Sketch, the following customary definitions of junction loss coefficients are introduced:

$$\Delta E = K \frac{V_o^2}{2g} \qquad (1)$$

$$\Delta P = K_p \frac{V_o^2}{2g} \qquad (2)$$

where ΔE is the energy head loss due to the junction, ΔP is the pressure head loss, K is the energy loss coefficient, K_p is the pressure loss coefficient, V_o is the mean velocity in the outlet pipe, and g

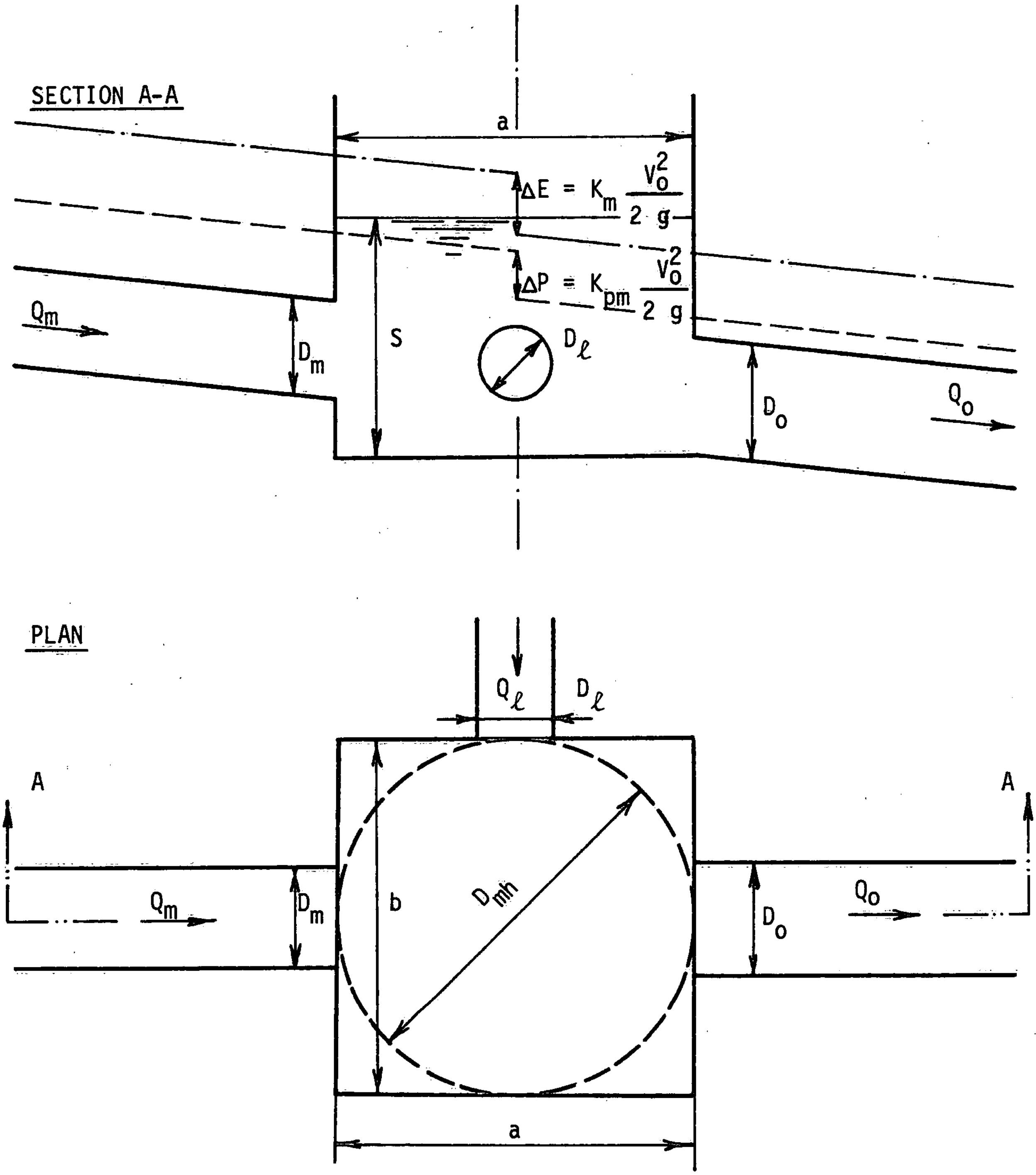


Fig.2. Junction Notation Sketch

is the acceleration due to gravity. It should be further explained that throughout this report, both energy and pressure loss coefficients are used. The former one is more common in fundamental considerations, the latter is then more convenient to use in practical applications involving calculations of the pressure gradient. Both coefficients may attain negative values and for that reason, they are sometimes also referred to as energy or pressure change coefficients. Furthermore, such coefficients can be derived for individual inflow pipes of the junction.

For a steady pressurized flow through a particular junction design which is further characterized by the junction benching, the head loss coefficient may be expressed as a function of 11 independent variables:

$$K = f_1 (\rho, \mu, Q_o, Q_\ell, S, g, a, b, D_m, D_\ell, D_o) \qquad (3)$$

where f_1 is a function, ρ is the fluid density, μ is the fluid viscosity, Q_o is the outlet pipe discharge, Q_ℓ is the lateral pipe discharge (the main pipe discharge $Q_m = Q_o - Q_\ell$), S is the water depth at the junction, a is the junction length, b is the junction width, and D_m, D_ℓ, D_o are the diameters of the main, lateral and outlet pipes, respectively. Dimensional analysis then yields the following expression for the head loss coefficient:

$$K = f_2 \left(\frac{Q_o}{g^{1/2} D_o^{5/2}}, \frac{\rho Q_o}{\mu D_o}, \frac{Q_\ell}{Q_o}, \frac{S}{D_o}, \frac{a}{D_o}, \frac{b}{D_o}, \frac{D_m}{D_o}, \frac{D_\ell}{D_o}\right) \qquad (4)$$

After substituting $V_o = 4Q_o/\pi D_o^2$ and $\nu = \mu/\rho$, the final expression for K is obtained:

$$K = f_3 \left(\frac{V_o}{\sqrt{g D_o}}, \frac{V_o D_o}{\nu}, \frac{Q_\ell}{Q_o}, \frac{S}{D_o}, \frac{a}{D_o}, \frac{b}{D_o}, \frac{D_m}{D_o}, \frac{D_\ell}{D_o}\right) \qquad (5)$$

Among the independent variables, the first four are flow characteristics and the last four describe the junction geometry. Note that a similar expression would be obtained for the pressure loss coefficient. The flow characteristic parameters can be identified, from left to right, as follows - the Froude number, the Reynolds number, the relative lateral inflow, and the relative junction submergence. For the three types of junctions investigated and certain flow conditions, eq. (5) may be further simplified. In particular, the previous experimental research permits the following simplifications:

(a) In pressurized flow, the coefficient K does not depend on the Froude number (15).

(b) For Reynolds numbers greater than 10^4, K does not depend on the Reynolds number (3). This condition is always met in practice, because specifications of the minimum sewer diameter (0.3 m) and the minimum flow velocity (0.6 m/s) yield Re numbers greater than 10^5.

(c) For submergence values larger than $S/D_o = 1.3$, K does not depend on the junction submergence.

Thus for $Re > 10^4$ and $S/D_o > 1.3$, a simplified relationship for K may be written as

$$K = f_4 \left(\frac{Q_\ell}{Q_o}, \frac{a}{D_o}, \frac{b}{D_o}, \frac{D_m}{D_o}, \frac{D_\ell}{D_o}\right) \qquad (6)$$

2.2 Model Similarity

In pressurized flow, energy or pressure change coefficients measured in model junctions are directly transferable to the prototype, if the independent dimensionless parameters listed in eq. (6) are identical in both the model and prototype. For identical relative lateral inflows, such identities can be easily achieved by operating a geometrically similar junction model in the region of $Re > 10^4$ and $S/D_o > 1.3$. Naturally, the condition of geometrical similarity applies to the junction benching as well.

To verify the transferability of head or pressure change coefficients observed in scale models, a limited attempt was made to investigate possible scaling effects for square-base manholes with a 90° bend and three different benching designs described later as moulds M1, M2 and M3. For this purpose, two junctions were built and tested for pressurized flow. The smaller junction was a 1:2 model of the larger installation. The pertinent test results are given in Table 1 - Head Loss Coefficients Obtained from Scaling Tests.

The deviations of head loss coefficients observed in both installations varied from -10% to +11%, with a mean deviation of about 2.5%. Thus within the realm of experimental uncertainties, no significant scaling effects were found.

In summary, it appears that scale-model investigations offer the best approach to the study of head losses at surcharged sewer pipe junctions. Such models should be geometrically similar to prototype junctions and operated in the region of $Re > 10^4$ and $S/D_o > 1.3$. If these conditions are met, the head or pressure change coefficients observed in the model are directly transferable to the prototype.

TABLE 1. HEAD LOSS COEFFICIENTS OBTAINED FROM SCALING TESTS

Junction Model	Head Loss Coefficient K			
	Benching			
	M1	M2	M3	Mean
Large Model Junction				
(a = b = 0.34 m; $D_m = D_\ell = D_o$ = 0.15 m)	1.73	1.47	0.89	1.36
Small Model Junction				
(a = b = 0.17 m; $D_m = D_\ell = D_o$ = 0.075 m)	1.63	1.32	0.99	1.31

3.0 EXPERIMENTAL PROGRAM

Observations of head losses at model sewer junctions were undertaken in three phases, each of which dealt with a different junction type. The first phase dealt with manholes with a 90° bend, the second phase dealt with the junctions of a main with a perpendicular lateral and, finally, the third phase dealt with junctions of two opposed laterals. Descriptions of experimental factors, apparatus and procedures follow.

3.1 Experimental Factors

Compared to the earlier studies, the main emphasis in this study was on studying the effects of junction benching on head losses and searching for ways to reduce these losses. Thus most of the experimental factors studied were junction geometrical parameters. The flow variables included the discharge through individual pipes and the division of flows among various lines. Most of the runs were done for pressurized flow. In addition, limited tests were made for open-channel flow.

The choice of junction geometries was largely based on the results of surveys of sponsor practices (11). In particular, the following junction parameters were varied: manhole base shape, manhole size, pipe size and benching at the junction. Further details follow.

The manhole base shape - The survey indicated that the round-base manholes are predominant in municipal practice. Square-base manholes are used by some Canadian municipalities, or in the case of larger pipes. Consequently, both manhole types, with round and square bases were studied.

The relative manhole size can be described by the ratio of the manhole characteristic cross-sectional dimension, either the diameter (D_{mh}) or the base width, to the outlet pipe diameter. The frequency of use of various manhole and pipe sizes has been established from the sponsors survey. Considering the sizes of the experimental pipes and junction manholes readily available, two basic D_{mh}/D_o ratios were obtained - 2.3 and 4.6. The smaller value corresponded closely to the maximum-size sewers installed in the most common standard manholes - 0.61 m (2 ft) pipes installed in the 1.22 m (4 ft) manholes. The larger value of D_{mh}/D_o corresponded to the commonly used minimum-size storm sewers (0.25 to 0.31 m, or 10 in to 12 in) installed in the standard 1.22 m (4 ft) manhole. It followed from the survey of sponsor practices that the above range of the relative manhole sizes would cover at least 2/3 of all design situations. The remaining design would be done mostly for larger non-prefabricated manholes whose relative sizes would be difficult to assess, but many of them would be still within the earlier mentioned range of relative manhole sizes.

Two pipe sizes were used in experimental runs - 75 mm and 152 mm. In most cases, the same pipe size was used in all branches and the main purpose of using two different pipe sizes in conjunction with one junction manhole was to obtain two different relative manhole sizes. For the junction of a main with a perpendicular lateral, some runs with a small lateral (75 mm) and the large main and outlet pipes were also conducted as discussed later.

In municipal design practice, it is customary to provide some benching at the junction manhole, in order to improve flow conditions at the junction and to reduce head losses. Up to five different benchings, referred to here as moulds, have been tested in various phases of the study. Detailed dimensions of such benchings are presented later pictorially for individual phases. A general description of individual benching designs designated as moulds M1 to M5 follows.

Mould M1 represented the simplest arrangement - the case with no benching or flow guidance at the junction. This arrangement was expected to produce the greatest head loss. Although the design without benching is not very common in practice, it was included as a limiting reference case.

Mould M2 was obtained by extending the lower half of the pipe through the junction and adding horizontal benches extending from the semicircular channel to the junction wall. In the plan, the channel axis follows a 90° segment of a circle with a radius equal to one half of the manhole diameter (or base dimension). This type of benching is fairly common in municipal practice and it should generally result in lower head losses than in the case of mould M1.

Mould M3 represents an improved variation of mould M2 obtained by extending the mould side walls to the pipe crown elevation. It should provide even more flow guidance and hence lower head losses than mould M2.

Mould M4 represents an improved variation of mould M3. By rounding the pipe edges at the junction entrance and exit, further reductions in head losses should be possible. This mould is not common in practice, although the square edges at both the pipe entry and exit are sometimes rounded, to some extent, in the field.

Mould M5 was proposed to further reduce head losses by improving the junction hydraulic efficiency. It includes the best features of mould M3 and, by expanding the flow cross-section throughout the junction, the flow velocity and the corresponding head loss at the junction are reduced. The changes in the pipe geometry were obtained by using eccentric pipe expanders/reducers of designs which can be implemented in the standard manufacturing process.

Although the above junction moulds do not exhaust all the possible geometries, they represent a wide range of conditions from the worst case (mould M1) to the best practical case (mould M5). Experimental data obtained for these five moulds can be used to make inferences for other designs.

3.2 Experimental Apparatus

A sketch of the experimental apparatus used in the first phase (manholes with a 90° bend) is shown in Fig. 3 - Experimental Apparatus (Phase 1). The apparatus consists of a water supply tank, the test pipes, the junction structure, and the outfall tank with a measuring weir.

Water discharging from a constant-head tank entered the water supply tank to which the main test pipe was connected. The water supply tank was designed to dampen out excessive turbulence in the flow discharging from the constant-head tank and to provide smooth inflow to the test pipe. The flow conditions in the main pipe were further improved by placing a honeycomb into the pipe inlet.

Two types of test pipes were used. The first one was a PVC pipe with an internal diameter of 152 mm (6 in). The second test pipe was a 75 mm (3 in) clear acrylic pipe. Both test pipes consisted of individual sections which were connected by rubber-sleeve couplings.

The test pipes were supported by a TV antenna beam resting on scissor jacks. These jacks were used to set the pipe slope. In pressurized flow tests, all pipes were set at a 1% slope. In open-channel flow tests the slope was 0.1%. Piezometer openings were formed by drilling 3 mm diameter holes in test pipes at 0.5 to 1.0 m intervals. Typically, up to 28 piezometer openings were connected to a manometer board which allowed the reading of the piezometric heads with an accuracy of ±0.5 mm. To avoid possible errors in piezometer readings caused by pressure fluctuations during the reading, slides of the manometer board were taken and analyzed at a later date.

The junction manhole was clear plexiglass. Two basic types were built - square- and circular-base manholes. The inside dimensions were 0.344 m x 0.344 m x 0.620 m (width x length x height) and the round-base manhole was formed by placing an insert inside the square manhole.

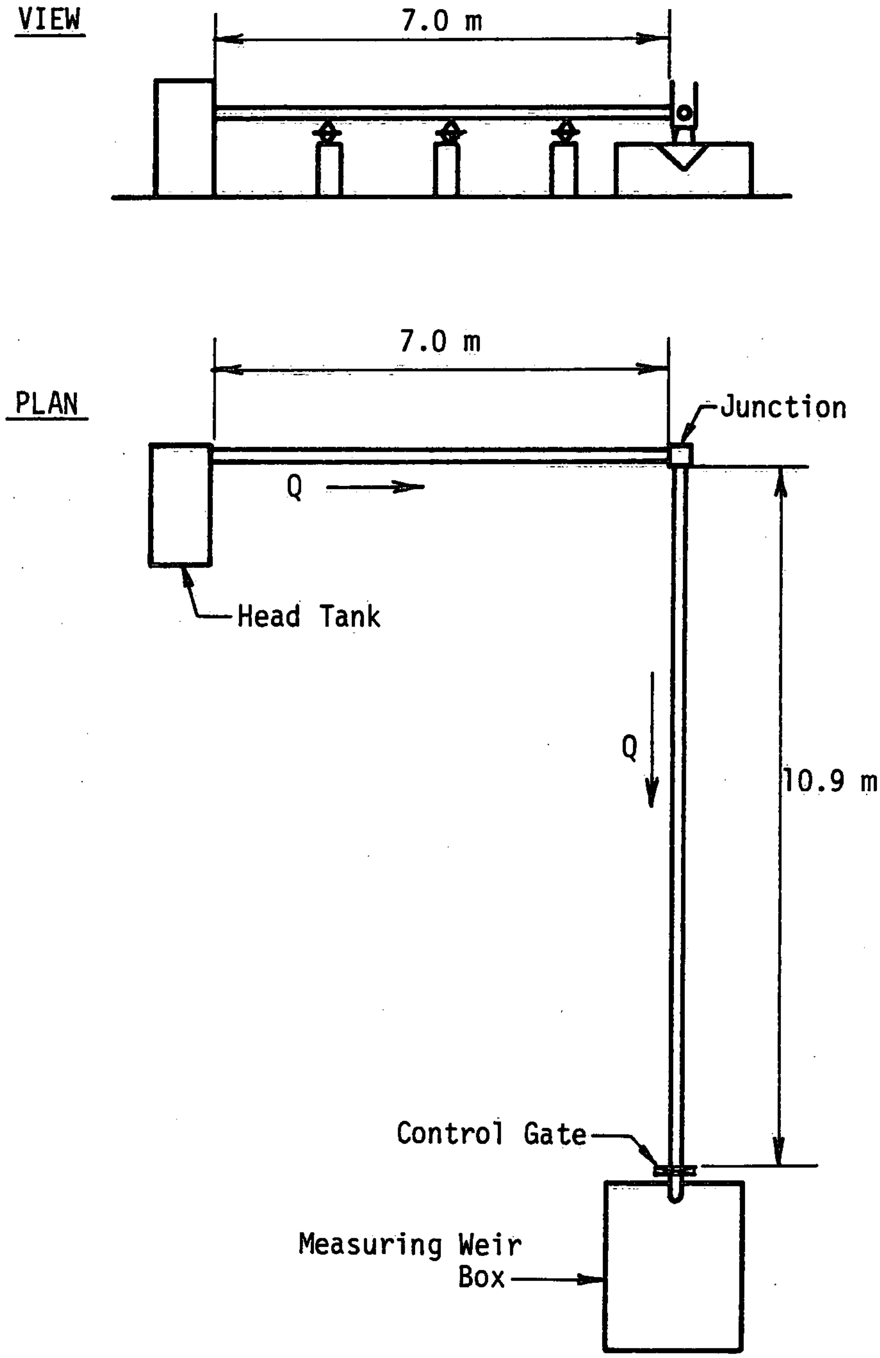


Fig.3. Experimental Apparatus(Phase 1)

An outlet weir box was installed at the downstream end of the outlet pipe equipped with a gate for varying the level of surcharge. Water leaving the outlet pipe discharged into the weir box with a 90° V-notch measuring weir.

3.3 Experimental Procedures

In preparation for experimental runs, a selected manhole with an internal mould was installed. Subsequently, the discharge and its division between the inflow pipes was varied in small increments over a wide range. In the pressurized flow experiments, the test pipe was surcharged and the hydraulic grade line reached elevations up to six pipe diameters above the crown. For the open-channel tests, the flow depth was varied from about half the pipe diameter to almost the pipe-full conditions. Once the flow through the installation was stabilized, piezometer readings were taken at the manometer board photographically and the discharge was measured by the measuring weirs. All the data were then processed by a computer program which calculated the total energy at individual points as $E = z + p/\gamma + V^2/2g$. Finally, the energy grade lines upstream and downstream of the junction were approximated by least-squares straight lines fitted through the points measured upstream and downstream of the junction. The differences between the upstream energy grade lines and the downstream grade line, at the junction axis, were taken as the energy head losses. An example of a typical experimental output is shown in Fig. 4 - Calculation of Head Losses from Observed Data.

For junctions with a 90° bend, individual measured head losses were plotted versus the velocity heads and the slope of the graph ΔE versus $(V_o^2/2g)$ was taken as the head loss coefficient (see Fig. 5 - Determination of the Head Loss Coefficient K). For junctions with two inflow pipes, the head losses were plotted versus the relative lateral inflow (Q_ℓ/Q_o) and the experimental points were approximated by regression curves used for further analysis.

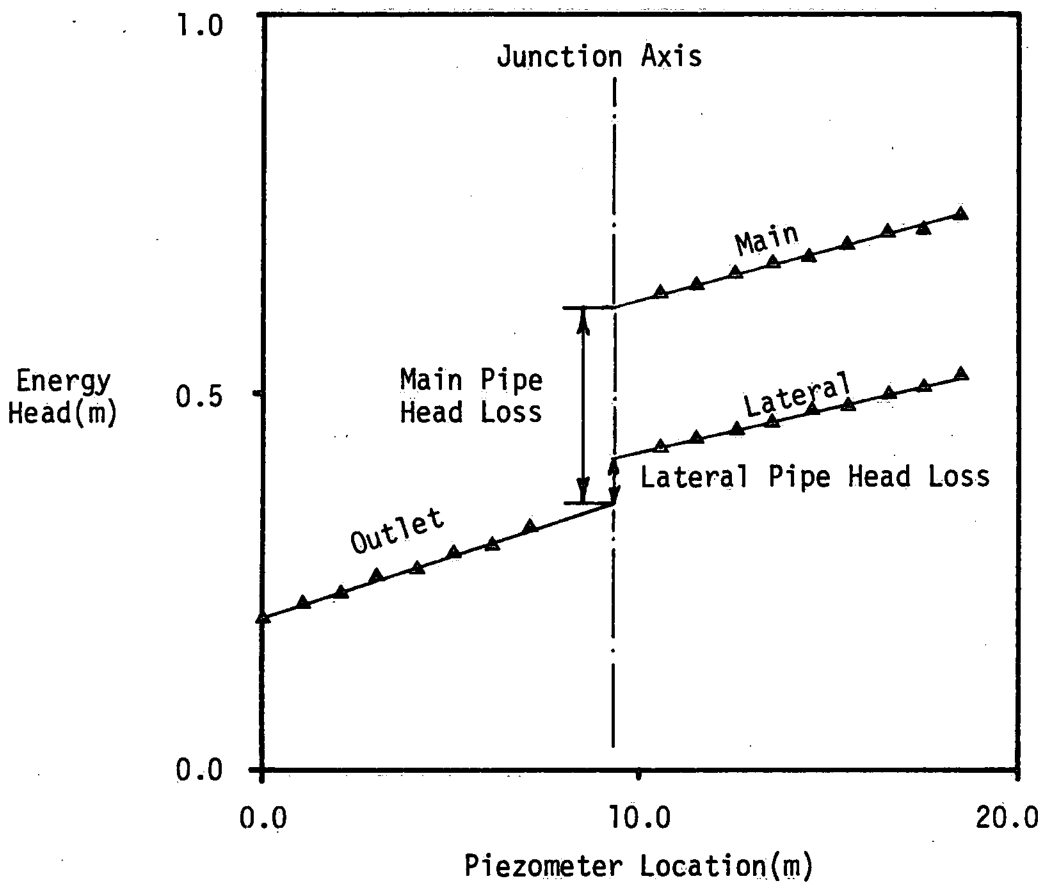


Fig.4. Calculation of Head Losses From Observed Data

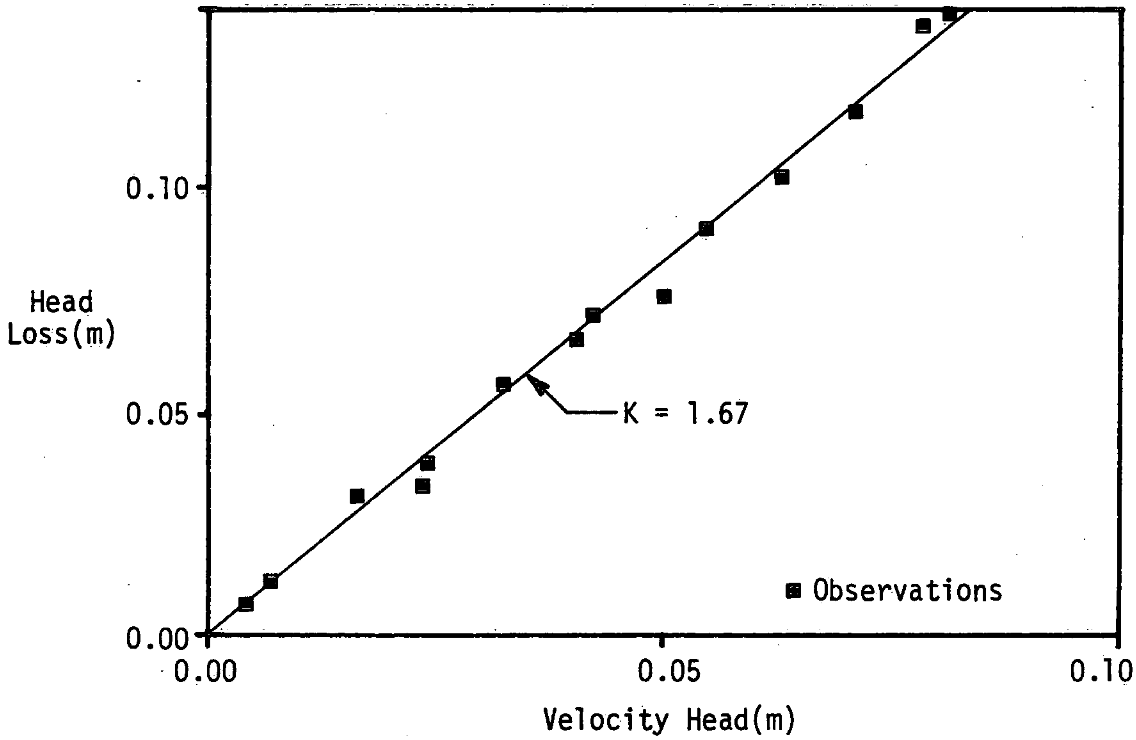


Fig.5. Determination of the Head Loss Coefficient K

4.0 RESULTS AND DISCUSSION

Results of experimental observations and their discussion are given in this chapter. The results are presented chronologically as they were produced during the study. Thus, the presentation starts with manholes with a 90° bend, followed by junctions of a main and a perpendicular lateral, and junctions with two opposed laterals.

4.1 Manholes with a 90° Bend

Manholes with a 90° bend are quite common in municipal practice and their investigation was assigned the highest priority by the study sponsors.

4.1.1 Previous Research

Sewer manholes with a 90° bend were investigated by Sangster et al. (15), Hare (6), and some of their results were further summarized by Black and Piggott (3).

Pressure loss coefficients published by Sangster et al. (15) were derived as a limiting case in studies of junctions of a main with a perpendicular lateral, when there is no discharge through the main pipe. Because of this limitation and the fact that only some values of the D_m/D_o and b/D_o ratios are of practical interest, namely 1.0 D_m/D_o 1.25 and 1.6 $b/D_o = D_{manh.}/D_o$ 8, only some Sangster's data are directly applicable in practice. It was inferred from such data that there was no difference observed in the performance of round and square base manholes. For the most common case of $D_m/D_o = 1.0$, $b/D_o = 2.00$ and mould M1, extrapolation of Sangster's data would yield the value of $K = 1.62$ which is similar to the values presented later in this section. The data further indicated that the head loss coefficient increased with the relative manhole width ratio (b/D_o) and decreased with the relative upstream pipe diameter (D_m/D_o).

Hare (6) presented results of tests dealing with various junction layouts. His configuration No. 10 resembles closely mould M1 tested here. Furthermore, he varied the outlet pipe size. The pertinent data are summarized in Table 2 - Pressure Change Coefficient for Manholes with a 90° Bend and Varying D_m/D_o. It is obvious from this table that the losses decrease with increasing outlet pipe diameter.

Black and Piggott (3) reanalyzed some of Sangster's and Hare's data and concluded that both the junction manhole geometry and the ratio D_m/D_o affected the losses at the junction.

TABLE 2. PRESSURE CHANGE COEFFICIENT FOR MANHOLES WITH A 90° BEND AND VARYING D_m/D_o (After ref. 6)

Upstream/Downstream Pipe Diameter Ratio D_m/D_o	Pressure Change Coefficient K_{pm}
0.7	1.50
0.8	1.65
0.9	1.75
1.0	1.85

4.1.2 Experimental Work

Experimental measurements were expressed in terms of both head and pressure loss coefficients, K and K_p. The relationship between both coefficients, for the manhole with a 90° bend, can be derived by writing the following relationship between the pressure and head losses (see Fig. 6 - Manhole with a 90° Bend):

$$\Delta P + \frac{V_m^2}{2g} = \Delta E + \frac{V_o^2}{2g} \qquad (7)$$

After substituting for ΔP and ΔE from eqs. (1) and (2), and $V_m = 4Q/\pi D_m^2$ and $V_o = 4Q/\pi D_o^2$, the final expression attains the form:

$$K_p = K + 1 - \left(\frac{D_o}{D_m}\right)^4 \qquad (8)$$

The experimental design was based on the earlier presented dimensional analysis which led to the derivation of eq. (5). This equation can be further simplified for the manhole with a 90° bend. In particular, there is no lateral inflow, thus the terms with D_ℓ and Q_ℓ are omitted. Furthermore, all experiments were done for a = b and $D_m = D_o$. Thus the simplified eq. (4) reads as follows:

$$K = f_5\left(\frac{V_o}{\sqrt{gD_o}}, \frac{V_o D_o}{\nu}, \frac{S}{D_o}, \frac{b}{D_o}\right) \qquad (9)$$

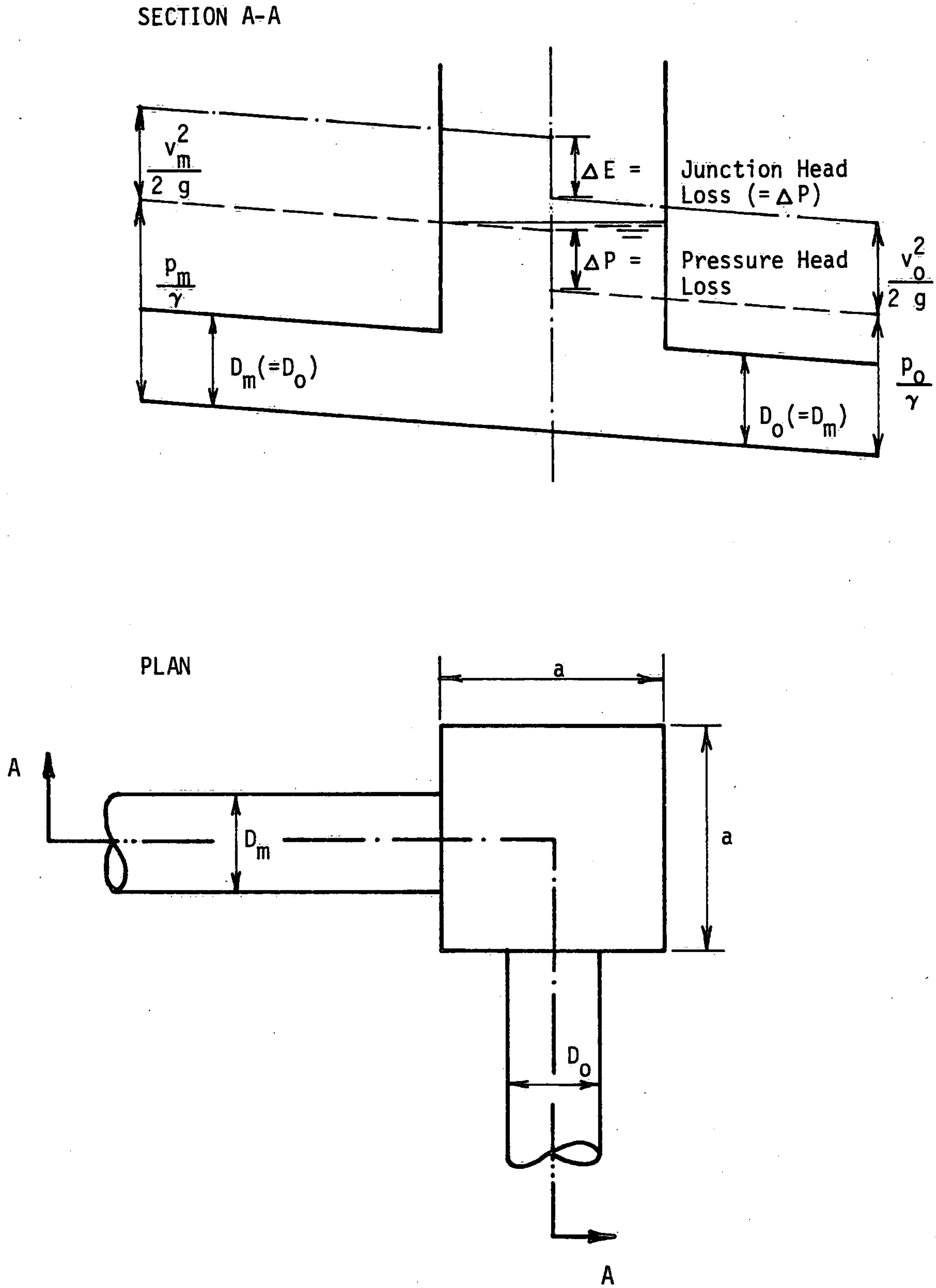


Fig.6. Manhole With a 90° Bend(D_m=D_o)

Equation (9) would apply to a particular manhole base shape (i.e., square or round) and the benching design. Both these purely geometric parameters can be added to the right side of eq. (9):

$$K = f_6 \left(\frac{V_o}{\sqrt{gD_o}}, \frac{V_o D_o}{\nu}, \frac{S}{D_o}, \frac{b}{D_o}, \text{base shape, benching}\right) \quad (10)$$

Further simplifications of eq. (10) are possible on the basis of supporting data produced by the earlier researchers as well as in this study. It was shown by Sangster <u>et al</u>. (15) that K does not depend on the Froude number in the region of pressurized flow. The same follows from Fig. 5 - Determination of the Head Loss Coefficient K, showing K's for a particular experimental series. Thus the Froude number can be omitted from further consideration.

The second independent variable in eq. (10) is the Reynolds number. Black and Piggott (3) reported that the head loss coefficients are not affected by Re for $Re > 10^4$. By keeping the Re number well above this value in all runs, the Reynolds number may be also omitted in the final data analysis.

The effects of submergence were investigated in a special series in which the depth at the junction was varied by operating the control at the downstream end of the installation. The results of these investigations are shown in Fig. 7 - Effects of Submergence on Head Loss Coefficient K, and indicate that the effects of submergence are negligible and can be also omitted in further analysis. Thus the simplified form of eq. (10), which indicates that K depends only on the junction geometry, may be written as follows:

$$K = f_7 \left(\frac{b}{D_o}, \text{base shape, benching}\right) \quad (11)$$

The experimental program comprised 27 series which are listed in Table 3 -Manholes with 90° Bend: Experimental Program and Results. Twenty series were done for pressurized flow, square and round manholes, two relative widths (b/D_o), and five benching designs. The last seven runs were done for open-channel flow just to explore the relative magnitude of losses under such conditions.

The manhole benchings tested are shown in Fig. 8 - Junction Designs Tested. The head loss coefficients are listed in Table 3 - Manholes with 90° Bend: Experimental Program and Results, and a further discussion of these coefficients follows.

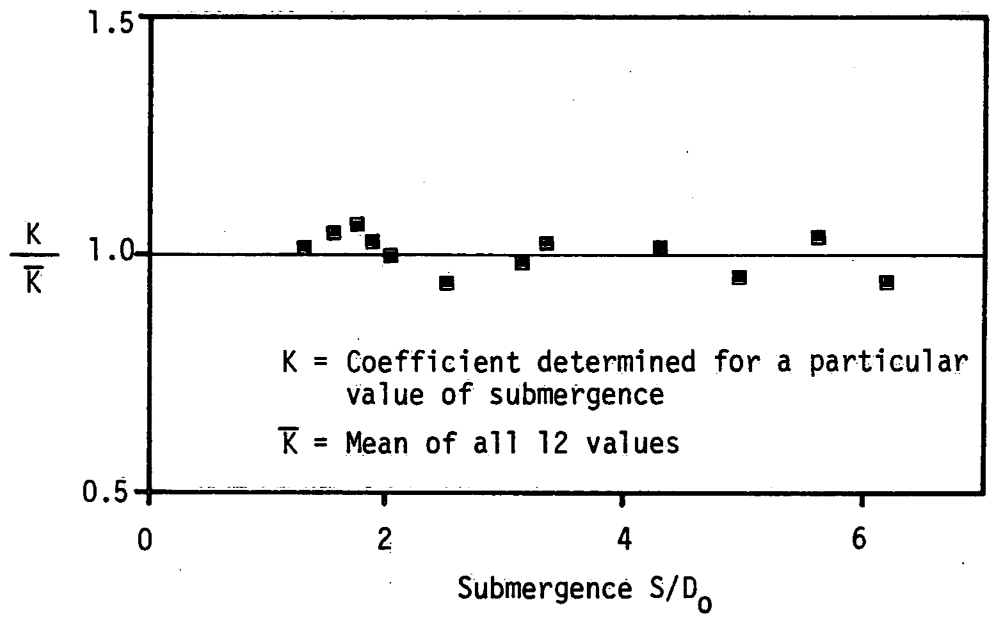


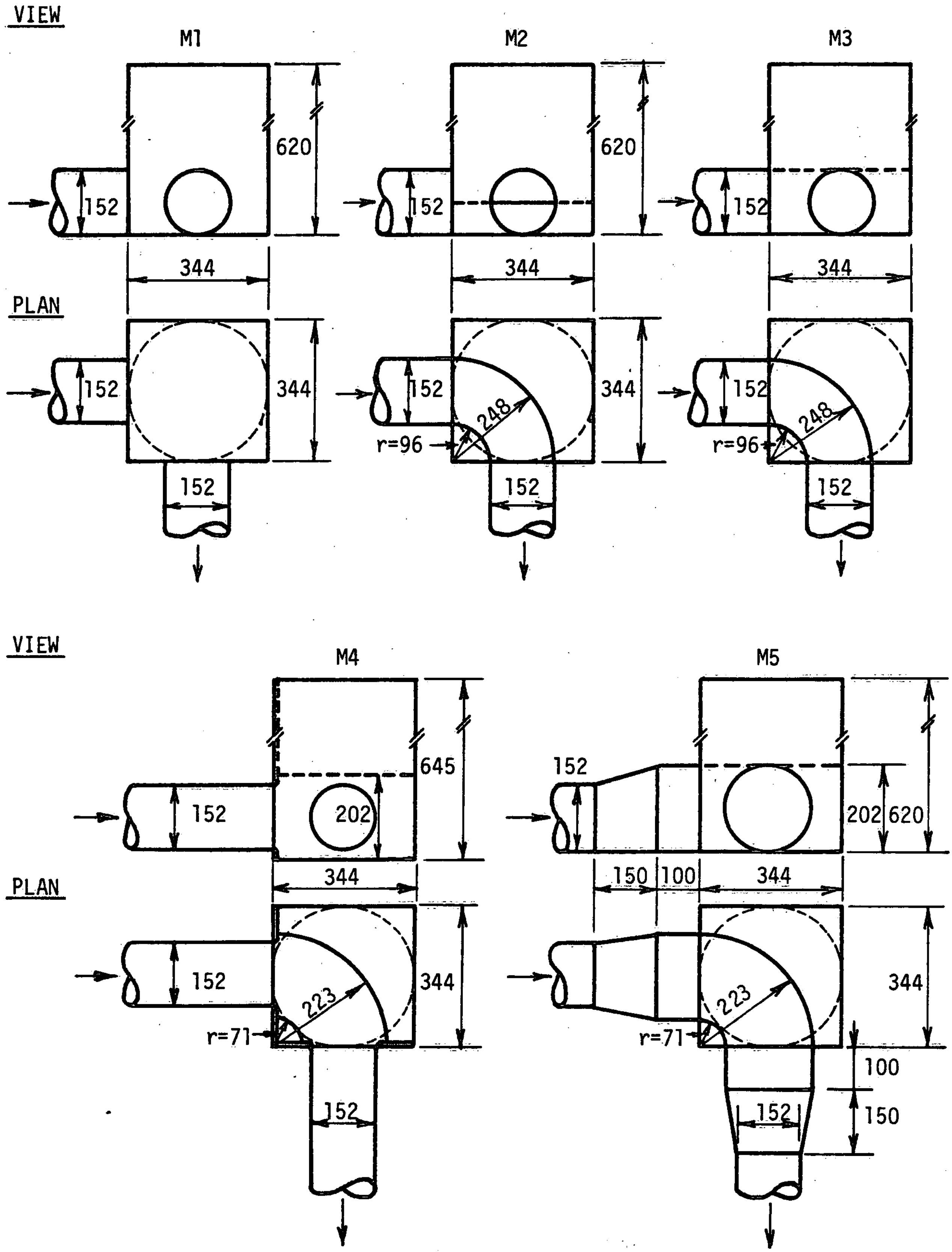
Fig.7. Effects of Submergence on Head Loss Coefficient K

TABLE 3. MANHOLES WITH 90° BEND - EXPERIMENTAL PROGRAM AND RESULTS

Run No.	Flow Type P = Pressure 0 = Open Channel	Manhole SQ = Square R = Round	Pipe Size L = Large S = Small	Mould	$K = K_p$
1	P	SQ	L	M1	1.73
2	P	SQ	L	M2	1.46
3	P	SQ	L	M3	0.88
4	P	SQ	L	M4	0.93
5	P	SQ	L	M5	0.52
6	P	SQ	S	M1	1.52
7	P	SQ	S	M1A	1.44
8	P	SQ	S	M2	1.69
9	P	SQ	S	M3	1.29
10	P	R	L	M1	1.80
11	P	R	L	M2	1.69
12	P	R	L	M3	0.97
13	P	R	L	M4	1.06
14	P	R	L	M5	0.55
15	P	R	S	M1	1.87
16	P	R	S	M2	1.67
17	P	R	S	M3	1.12
18	P	SQ	S	M1	1.67
19	P	SQ	S	M2	1.41
20	P	SQ	S	M3	0.98
21	0	SQ	L	M1	1.08
22	0	SQ	L	M2	0.58
23	0	SQ	L	M3	0.27
24	0	SQ	L	M4	0.68
25	0	SQ	L	M5	0.34
26	0	R	L	M1	0.97
27	0	R	L	M2	0.46

4.1.3 Pressurized Flow Results

The head losses in pressurized flow were investigated most extensively, because such conditions are of primary interest to sewer designers. In all experiments, significant head losses were observed at the junction. Although the pressure fluctuations in pipe sections were relatively small, large agitation of the water surface at the



All dimensions are in millimeters(25.4mm=1 inch)

Fig.8. Junction Designs Tested (D = 152 mm)

junction manhole was observed. Under some conditions, a surface roller (similar to that occurring in a hydraulic jump) developed at the junction. Large eddies and vortices generated at the junction then affected the flow conditions in the downstream pipe. Such flow conditions were characterized by secondary helical currents. Effects of individual experimental factors are discussed below.

Manhole Base Shape

Within the range of experimental conditions studied, the effect of the manhole base shape was minimal. Considering all the paired results (i.e., for square and circular base) in Table 3 - Manholes with 90° Bend: Experimental Program and Results, for various moulds and pressurized flow, the average head loss coefficients for square and circular manholes were 1.25 and 1.31, respectively. Such a difference is hardly significant. For individual moulds, the largest deviation found was about 20%. Thus, it can be concluded that both types of manhole bases tested produced about the same head losses. The round-base manholes produced loss coefficients about 5% larger than those found for square-base manholes. Such results are consistent with the earlier finding of Sangster et al. (15) who simply grouped square and round manhole results together.

Relative Manhole Size

The relative manhole size is described here by the ratio of the manhole diameter (or the base dimension of a square manhole) D_{mh} to the outlet pipe diameter D_o. In total, six comparative runs were conducted for two values of the D_{mh}/D_o ratio - 2.3 and 4.60. As mentioned earlier, these two ratio values were selected on the basis of a survey of municipal practices.

The observed results were barely sensitive to the variation in the D_{mh}/D_o ratio. In general, the head loss increased with an increasing relative junction manhole size. It is believed that smaller manholes are more effective in deflecting the flow into the exit pipe. It seems plausible that the head losses would be more affected by the D_{mh}/D_o ratio in the region of the lower values of this ratio, as indicated by Sangster's (15) results. In that study, the lowest head losses were observed in manholes which were slightly wider (by 5%) than the pipe. Such losses were about 18% lower than those observed for the D_{mh}/D_o ratio of 1.9 which is comparable to the lower value employed in this study. It should be stated, however, that the $D_{mh}/D_o < 2.0$ values are of little interest in practical design. Within the range of common D_{mh}/D_o values, 2 D_{mh}/D_o 6, the head losses seem barely affected by the relative manhole size (width).

Manhole Benching

The manhole benching affected strongly the observed junction head losses. In fact, among the experimental factors studied, the benchings inside junctions, referred to here as moulds, had the most pronounced effect on the head loss. By providing flow guidance at the junction, some flow momentum is preserved and the head losses are reduced. The first four moulds studied were designed to gradually improve the flow guidance at the junction. Taking the mould M1 as the reference, the common municipal designs M2 and M3 (see Fig. 8 - Junction Designs Tested) reduced the head loss by 15% and 46%, respectively. In other words, the largest head loss coefficient observed, 1.75 (M1), was reduced to 1.5 for M2, and to 0.95 for M3. The relatively small improvement brought about by mould M2 was surprising. Detailed observations of the operation of this mould revealed that it deflected the incoming stream upwards and caused large agitation and head loss at the junction.

A further attempt to improve mould M3 by rounding the exit and entrance pipe edges was counterproductive. The head loss for the resulting mould M4 was even slightly larger than that for mould M3, but this minor deviation (0.04) was not statistically significant.

The final attempt to reduce the head loss at the junction by improved geometry is represented by mould M5. This mould incorporates several beneficial features which lead to reduced losses. Firstly, the flow guidance is provided at the junction by a benching extending above the test pipe crown elevation. Furthermore, the pipe cross-section upstream of the junction is expanded and this results in two additional benefits - the effective relative manhole size (D_m/D_o) is reduced and the flow velocity at the junction, in the channel provided, is also reduced. Both these features result in smaller losses. Mould M5 reduced the original loss (M1) from 1.75 to 0.54, or by about 70%. Compared to the municipal designs M2 and M3, mould M5 still represents a significant improvement.

When examining mould M5, the pipe transitions may seem to be relatively sharp and somewhat crude. Such a design, however, reflects the procedures used in manufacturing these transitions from sections of concrete pipes. These procedures impose constraints on further possible improvements in streamlining this transition. The application of mould M5 in practice will be also affected by cost considerations. The transition sections required for mould M5 are generally hand-made and the associated increase in costs may limit the use of this mould. There will be, however, design situations where the need to reduce the head loss may call for the use of this mould and override the cost considerations.

The last mould tested was referred to as mould M1A. This mould represents a minor variation of the reference mould M1. Such a variation was obtained by bringing the back junction wall (opposite the flow entrance) forward in order to align it with the exit pipe. This arrangement improves the energy recovery at the junction and slightly reduces the head loss (by 5%). The same idea could be implemented in conjunction with all the other moulds.

4.1.4 Open-Channel Flow Results

Limited investigations of junction losses in open-channel flow were also included in the experimental program. As per instructions from the Steering Committee, the main objective of these investigations was to compare the relative magnitude of losses in the open-channel flow to those extablished earlier for pressurized flow. Towards this end, seven experimental series were done as outlined in Table 3 - Manholes with 90° Bend: Experimental Program and Results. All these runs were made for the larger pipe. Only square manholes were tested for all the moulds M1 to M5. For round manholes, only moulds M1 and M2 were tested. The remaining installations of moulds M3 to M5 would be, in the open-channel flow region, identical to those tested for square manholes.

The results reported in Table 3 - Manholes with 90° Bend: Experimental Program and Results, for open-channel flow conditions were significantly less consistent than those reported earlier for pressurized flow. The observed coefficients were always smaller than their counterparts corresponding to the pressurized flow. This was expected, because the changes in the flow cross-sectional area, encountered in the open-channel flow region at the junction, are smaller than those encountered in the pressurized flow experiments. The highest loss was observed for the reference mould M1 - 1.08. The loss coefficients for municipal designs M2 and M3 ranged from 0.27 (for M3) to 0.58 (for M2). The loss coefficient established for mould M4 was exceptionally small - 0.07. It is believed that this value was strongly affected by the experimental data scatter. Finally, mould M5 yielded a loss coefficient of 0.34. With the exception of mould M4, the results found for the remaining four moulds correspond quite well to the degree of changes in the flow areas at junctions with various moulds.

4.1.5 Sulphide Gas Releases

One of the concerns in sanitary sewer junction design indicated by the study sponsors is the release of sulphide gases at junctions (11). Although such releases could not be directly studied in the experimental apparatus employed, some inferences about these releases can be made on the basis of visual observations of flow conditions at the junction. Flow turbulence and agitation are the main reason for gas releases at junctions.

To evaluate the susceptibility of various junction designs to sulphide gas releases, a somewhat subjective classification system was established and presented in Table 4 - Rating of Susceptibility to Sulphide Gas Releases.

TABLE 4. RATING OF SUSCEPTIBILITY TO SULPHIDE GAS RELEASES

Rating	Agitation and Turbulence at the Junction	Junction Susceptibilty to Sulphide Gas Releases
1	Low	Low
2	Medium	Medium
3	High	High

Using the above ratings, the operation of various junction designs tested is assessed in Table 5 - Evaluation of Various Junction Designs for Sulphide Gas Releases.

TABLE 5. EVALUATION OF VARIOUS JUNCTION DESIGNS FOR SULPHIDE GAS RELEASES

Manholes		Ratings Mould (Benching)				
		M1	M2	M3	M4	M5
Round Manholes:	$D_{mh}/D_o = 2.3$	3	3	1	1	1
	$D_{mh}/D_o = 4.6$	3	3	1	-	-
Square Manholes:	$b/D_o = 2.3$	3	3	1	1	1
	$b/D_o = 4.6$	2	3	1	-	-

It is obvious from Table 5 that the manhole benching strongly affects turbulence and the concomitant sulphide releases at the junction. If such releases are expected to cause problems, mould M3 (or even M4 or M5) with benching reaching to the pipe crown should be used. Designs M1 and M2 were both found deficient with regard to generation of turbulence and possible sulphide gas releases at the junction.

4.1.6 Design Data

For practical design, the experimental data presented earlier in Table 3 - Manhole with 90° Bend: Experimental Program and Results, can be rounded off and further extrapolated to the cases which have not been studied. The basic design data are presented for pressurized flow and no change in pipe diameter ($D_m = D_o$), followed by correction coefficients for cases with a change in pipe diameter, and open-channel flow data.

Design Data for Manholes With a 90° Bend

(1) Pressurized Flow

(a) No change in pipe diameter ($D_m = D_o$), both square- and round-base manholes - the data are listed below in Table 6 - Head Loss Coefficients for Design of Manholes with 90° Bend.

TABLE 6. HEAD LOSS COEFFICIENTS FOR DESIGN OF MANHOLES WITH 90° BEND

Mould (Benching)	Head (= Pressure) Loss Coefficient Smaller Manholes ($D_{mh}/D_o = b/D_o = 2.3$)	Larger Manholes ($D_{mh}/D_o = b/D_o = 4.6$)	Smaller and Larger Manholes Combined
M1	1.7	1.8	1.75
M2	1.6	1.7	1.65
M3	1.0	1.2	1.10
M4	1.0	1.1	1.05
M5	0.6	0.7	0.65

(b) Approximate correction for changes in pipe diameter. When the outlet diameter D_o exceeds the inlet diamter D_m, the pressure loss coefficient can be corrected as follows (6):

$$K_{p(D_m/D_o)} = C\, K_{(D_m/D_o = 1)} \tag{12}$$

where the correction coefficient C values are listed in Table 7 - Correction Coefficient for Manholes with 90° Bend and Different Main and Outlet Sizes.

TABLE 7. CORRECTION COEFFICIENT FOR MANHOLES WITH 90° BEND AND DIFFERENT MAIN AND OUTLET SIZES

D_m/D_o	0.7	0.8	0.9	1.0
C	0.81	0.89	0.95	1.0

The corrected head loss coefficient is then calculated from eq. (8).

(2) <u>Open-Channel Flow</u>

Recognizing the uncertainties inherent to the experimental data, the coefficients listed in Table 8 - Approximate Head Loss Coefficient for Open-Channel Flow Through Manholes with 90° Bend, below are recommended for junctions operating in subcritical open-channel flow. These coefficients apply to both square and round manhole and cases with no changes in pipe diameter.

TABLE 8. APPROXIMATE HEAD LOSS COEFFICIENT FOR OPEN-CHANNEL FLOW THROUGH MANHOLES WITH 90° BEND

	Mould (Benching)				
	M1	M2	M3	M4	M5
Head Loss Coefficient	1.1	0.6	0.3	0.3	0.3

4.1.7 Design Examples

To illustrate the use of the design data given in the preceding section, several simple examples are presented below.

Example No. 1

Calculate the head loss at a surcharged manhole with a 90° bend for the following given data:

Upstream sewer diameter (D_m) = 0.61 m (24 in)

Downstream sewer diameter (D_o) = 0.61 m (24 in)

Discharge - 0.584 m^3/s (20.6 cfs)

Manhole type - a round-base manhole, 1.22 m (4 ft) in diameter

Manhole benching - Type M3.

Step 1 - Calculate the outlet sewer velocity head H_o as

$$H_o = V_o^2/2\,g \quad \text{where} \quad V_o = Q/\pi D_o^2/4$$

$$V_o = \frac{0.584}{\frac{3.14 \times 0.61^2}{4}} = 2.0 \text{ m/s (6.55 fps)}$$

$$H_o = 2.0^2/2 \times 9.81 = 0.204 \text{ m (0.67 ft)}$$

Step 2 - Determine the head loss coefficient from data in Table 6. For pressurized flow and smaller manholes (D_{mh}/D_o = 2.0), determine the head loss coefficient as K (=K_p) = 1.0

Step 3 - Calculate the head loss as

$$\Delta E = K\,H_o = 1.0 \times 0.204 = 0.204 \text{ m (0.67 ft)}$$

Thus, the head loss at the junction manhole is 0.204 m (0.67 ft). Such a head loss can be compensated for by dropping the invert elevation between the inlet and outlet by the same amount - 0.204 m.

Example No. 2

Repeat the calculations in Example No. 1 for a larger outlet sewer diameter (D_o = 0.686 m = 27 in).

Step 1 - Determine the pressure loss coefficient K_p for D_m/D_o = 0.61/0.686 = 0.89. From eq. (12),

$$K_{p_{D_m/D_o = 0.89}} = C\, K_{p_{D_m/D_o = 1}}$$

where C is determined from Table 7 and $K_{p_{1.0}}$ is the same as in the previous example. Thus,

$$K_{p_{0.89}} = 0.94 \times 1.0 = 0.94$$

Step 2 - Determine the pressure loss for the above K_p and the outlet diameter D_o = 0.686 m (27 in). The velocity head for the outlet is calculated as

$$H_o = V_o^2/2\,g \quad \text{where} \quad V_o = Q/A_o =$$

$$0.584/0.370 = 1.58 \text{ m/s (5.18 fps)}$$

$$H_o = 1.58^2/2 \times 9.81 = 0.127 \text{ m (0.42 ft)}$$

$$\Delta P = K_p \times H_o = 0.94 \times 0.127 = 0.119 \text{ m (0.39 ft)}$$

Step 3 - Determine the head loss coefficient using eq. (8)

$$K = K_p - 1 + \left(\frac{D_o}{D_m}\right)^4$$

$$K = 0.94 - 1 + (1/0.89)^4 = 0.94 - 1 + 1.59 = 1.53$$

Step 4 - Determine the head loss as $\Delta H = K \times H_o$ = 1.53 x 0.127 = 0.195 m (0.64 ft).

Thus, the expansion of the outlet diameter from 0.61 m (24 in) to 0.686 m (27 in) resulted in a minor reduction in the manhole head loss - from 0.204 m (0.67 ft) to 0.195 m (0.64 ft).

Example No. 3

Estimate the head loss at the manhole considered in Example No. 1 for Q = 0.400 m^3/s (14.1 cfs) and a subcritical open-channel flow. The depth of flow in the outlet sewer is h = 0.55 m (1.85 ft).

<u>Step 1</u> - Determine the velocity head as $H_o = V_o^2/2g$ where

$$V_o = Q/A = 0.400/0.2767 = 1.45 \text{ m/s } (4.74 \text{ fps})$$

$$H_o = 1.45^2/2 \times 9.81 = 0.107 \text{ m } (0.35 \text{ ft})$$

<u>Step 2</u> - Using the coefficient K (for M3) from Table 8, calculate the head loss as

$$\Delta E = K \times H_o = 0.3 \times 0.107 = 0.032 \text{ m } (0.11 \text{ ft})$$

Thus, in open-channel flow, the head loss is only 0.032 m (0.11 ft).

4.1.8 Summary

The principal findings of the first phase dealing with head losses at manholes with a 90° bend can be summarized as follows:

(1) Head and pressure losses at surcharged junctions with a 90° angle change in the pipe alignment are affected by both the flow velocity and the junction geometry. The loss increases linearly with the velocity head and the coefficient of proportionality is the head loss coefficient.

(2) Among the junction geometrical parameters, the benching (mould) had the most pronounced effect on the head loss, followed by the relative manhole size (width), and the base shape. The lowest head losses were found for mould M5 which represented a definite improvement in comparison to the municipal designs M2 and M3. Compared to the design without any benching (M1), the design with benching at half the pipe diameter (M2) brought about only an insignificant reduction in losses. The full benching at the pipe crown (M3), however, reduced the losses significantly. Observed head losses were barely sensitive to the variations in the relative manhole size tested. Smaller manholes produce somewhat smaller head losses, because they deflect better flow into the exit pipe. The losses observed for square- and round-base manholes were, on the average, almost identical.

(3) Limited scaling tests with two models of different scales produced comparable head loss coefficients. No significant scaling effects can be deduced from the observed data.

(4) Measurements of head losses in the open-channel flow were less consistent than those conducted for pressurized flow. In general, the observed losses were always significantly smaller than those corresponding to the pressurized flow. The losses were again affected by the junction mould. Benchings installed at the junction, such as those described by moulds M2, M3, M4 and M5, significantly reduced the junction head loss.

4.2 Junction Manholes of a Main with a Perpendicular Lateral

Junctions of a main with a perpendicular lateral were studied in the second phase of the study (12). Such junctions are fairly common in design practice.

4.2.1 Previous Research

Junctions of a main with a perpendicular lateral were investigated by de Groot and Boyd (5), Lindvall (9), Prins (14), Sangster et al. (15), and Yevjevich and Barnes (16). Additional references were found for pipe T-junctions without manholes, as used e.g., in water distribution networks. The latter references are not relevant to sewer junctions which have a free water surface at the junction.

de Groot and Boyd's data (5) refer to junctions without any benching. The loss coefficients were found to depend only on the flow division between the main and the lateral and increased with an increasing lateral inflow.

Lindvall's data (9) were produced for manholes with benchings somewhat similar to moulds M2 and M3 used in this study. The pressure loss coefficients K_p's were somewhat modified so they cannot be used directly in design. The modified coefficients depended only on the flow division ratio, the relative lateral pipe diameter and the manhole diameter.

Prins (14) studied head losses at junctions with a main and a lateral for open-channel flow conditions. He reported the highest losses for junctions without any benching and the 90° alignment of the lateral. Such head losses were reduced by using benching reaching to the pipe crown inside the manhole and by reducing the alignment angle to 45°.

Sangster et al. (15) reported fairly extensive tests of junctions discussed here. In their experiments, the relative lateral discharge Q_r $(=Q_\ell/Q_o)$ was the main independent variable and the effects of the relative pipe diameters and the relative junction width were also noted. All experiments were done for pressurized flow.

Yevjevich and Barnes (16) evaluated head losses at a junction of a main pipe, with a free flow, and a perpendicularly aligned lateral. The junction box was rather narrow, just slightly wider than the main pipe, and the lateral pipe diameter was 0.3 of the main pipe diameter. Power losses attributable to the junction were expressed by a regression equation which indicated that the junction power loss was a function of the relative discharge Q_ℓ/Q_m and the relative pipe diameter D_ℓ/D_o. Neither the junction geometry nor the results are directly applicable to sewer design.

In summary, it appears that head losses at junctions with a main pipe and a lateral are affected by the lateral pipe alignment angle; the relative sizes of the main, lateral and outlet pipes; the benching at the manhole; and, the relative discharge Q_r. Any new investigations should consider such variables and concentrate on junctions with geometries reflecting the current practices.

4.2.2 Experimental Work

A definition sketch for the junction of a main with a perpendicular lateral is shown in Fig. 9 - Junction of a Main with a Perpendicular Lateral. Various benchings tested are shown in the same figure.

Head losses at junctions of a main with a lateral were again determined experimentally and expressed by means of the earlier introduced loss coefficients K and K_p. In this case, two types of loss coefficients are discerned - for the main and the lateral. Such coefficients are defined as follows:

Head loss coefficients:

Main pipe $$K_m = \frac{\Delta E_m}{\frac{V_o^2}{2g}} = \frac{E_{jm} - E_{jo}}{\frac{V_o^2}{2g}} \qquad (13)$$

Lateral pipe $$K_\ell = \frac{\Delta E_\ell}{\frac{V_o^2}{2g}} = \frac{E_{j\ell} - E_{jo}}{\frac{V_o^2}{2g}} \qquad (14)$$

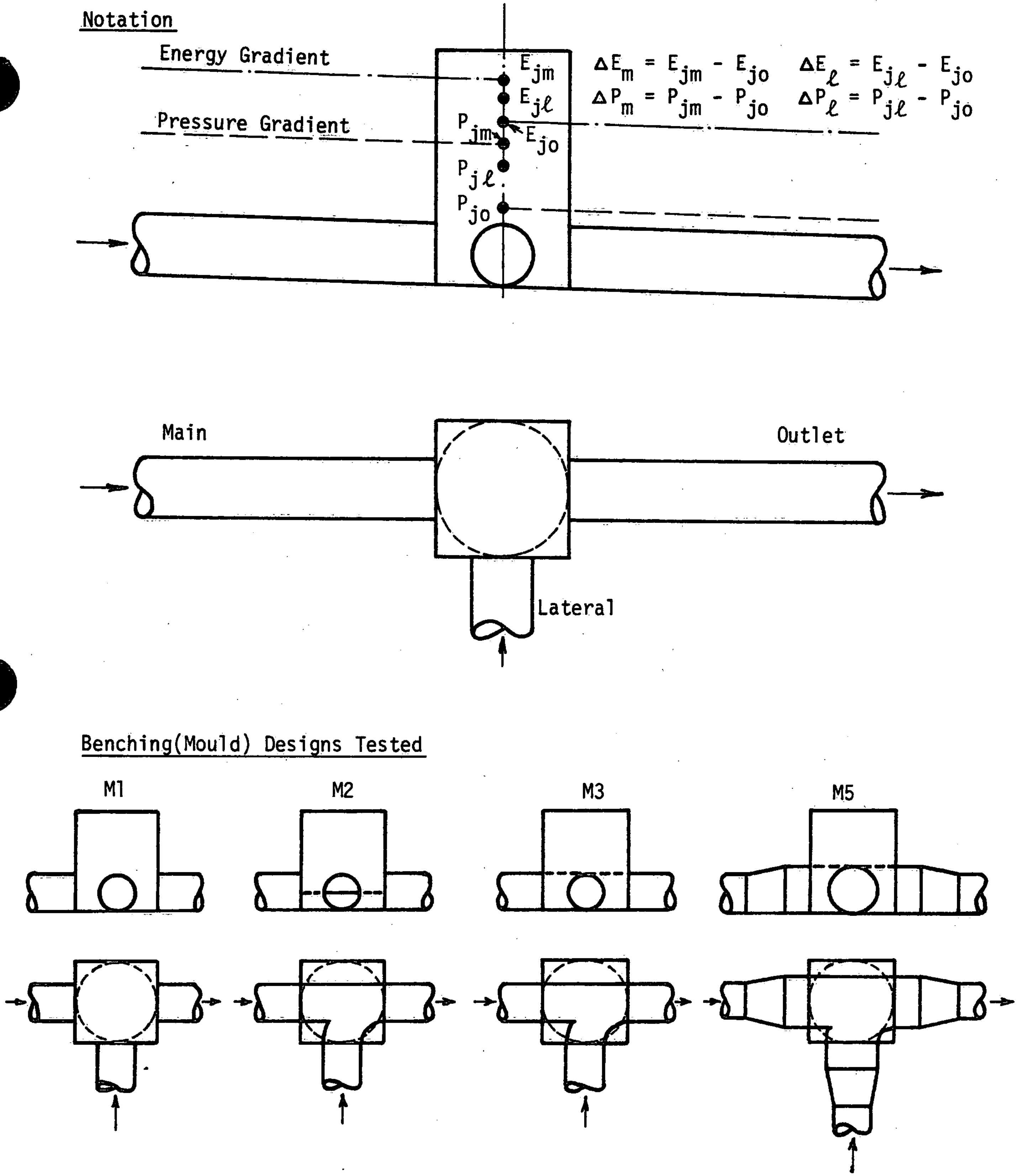


Fig.9. Junction of a Main With a Perpendicular Lateral

Pressure loss (change) coefficients:

Main pipe $$K_{pm} = \frac{\Delta P_m}{\frac{V_o^2}{2g}} = \frac{P_{jm} - P_{jo}}{\frac{V_o^2}{2g}} \tag{15}$$

Lateral pipe $$K_{p\ell} = \frac{\Delta P_\ell}{\frac{V_o^2}{2g}} = \frac{P_{j\ell} - P_{jo}}{\frac{V_o^2}{2g}} \tag{16}$$

where E and P are the energy and pressure gradient elevations projected to the junction centre, respectively, and subscripts m, ℓ, o and j refer to the main, lateral, outlet, and junction centre, respectively. Some researchers introduce even a third coefficient, K_w, for the water surface level at the junction (3).

Equation (5) lists the experimental variables for the head loss coefficient for the pressurized junction of a main with a perpendicular lateral. It follows from the earlier experimental work (3,15) that eq. (5) can be further simplified by omitting those independent variables which do not affect the loss coefficients. Such variables include the Froude number, the Reynolds number (for $Re > 10^4$), and the submergence ratio (S/D_o). On the other hand, two additional terms can be added - those describing the junction benching and the base shape. Thus, the final expression for the head loss coefficient can be written as:

$$K = f_8 \left(\frac{Q_\ell}{Q_o}, \frac{b}{D_o} \left(\text{or } \frac{D_{mh}}{D_o}\right), \frac{D_m}{D_o}, \frac{D_\ell}{D_o}, \text{benching, base shape}\right) \tag{17}$$

It is of interest to note that among the six independent variables in eq. (17), only one, Q_ℓ/Q_o, is a hydraulic variable and the remaining describe the junction geometry. In individual runs, the independent variables were varied as shown in Table 9 - Junctions of a Main with a Perpendicular Lateral: Experimental Program. It should be mentioned that because of budget limitations, $D_m/D_o = 1$ in all runs. Expressions for all four K's (see eqs. (13) to (16)) would be analogous to eq. (17).

After considering the existing data on junctions with a main and a lateral, an experimental program was designed to provide new information on this type of junction and to explore practical means of reducing losses at such junctions. This program consisted of 24 experimental runs in which the following experimental factors were varied:

- Type of flow - free flow or pressurized
- Relative lateral discharge - defined as $Q_{lateral}/Q_{outflow}$ (Q_ℓ/Q_o)
- Relative manhole size (b/D_o, or D_{mh}/D_o)
- Relative pipe sizes (D_ℓ/D_o, $D_m/D_o = 1$)
- Benching at the junction -described as moulds M1, M2, M3, and M5; and,
- Manhole base shape - square or round.

Further discussion of individual experimental variables follows.

TABLE 9. JUNCTIONS OF A MAIN WITH A PERPENDICULAR LATERAL - EXPERIMENTAL PROGRAM

Run No.	Flow Type P = Pressure O = Open Channel	Manhole Base SQ = Square R = Round	Pipe Size L = Large S = Small	Mould
1	P	SQ	L	M1
2	P	SQ	L	M2
3	P	SQ	L	M3
4	P	SQ	L	M5
5	P	R	L	M1
6	P	R	L	M2
7	P	R	L	M3
8	P	R	L	M5
9	O	SQ	L	M1
10	O	SQ	L	M2
11	O	SQ	L	M3
12	O	SQ	L	M5
13	O	R	L	M1
14	O	R	L	M2
15	P	SQ	S	M1
16	P	SQ	S	M2
17	P	SQ	S	M3
18	P	R	S	M1
19	P	R	S	M2
20	P	R	S	M3
21	P	SQ	L/S	M1
22	P	SQ	L/S	M2
23	P	SQ	L/S	M3
24	P	SQ	L/S	M5

Experiments were done for both free and pressurized flows, with the emphasis put on the latter. The earlier research indicated that the head losses in free flow are much smaller than in the pressurized flow and the spacing of junctions under free flow conditions may influence the results.

For both types of flow, the relative lateral flow Q_ℓ/Q_o was varied from zero to one in all experimental runs.

The relative manhole size is described by the ratio b/D_o or D_{mh}/D_o, depending on the manhole base shape. As discussed earlier, two values of this ratio were used - 2.3 and 4.6. This was achieved by changing the pipe sizes.

Two pipe sizes were used in the experiments - 75 and 152 mm. In all runs, the main and outlet diameters were identical (D_m/D_o = 1). Two relative sizes of the lateral pipe were used - D_ℓ/D_o = 0.5 and 1.0.

In the current municipal practice, benchings at junctions are provided to improve access to the manhole, facilitate maintenance, and improve flow conditions at the junction and thereby reduce the head losses. Altogether, four different benching designs, referred to here as moulds, were tested in this phase. All the moulds tested are shown in Fig. 9 - Junction of a Main with a Perpendicular Lateral, and further described below. For consistency with the earlier phase, the same mould designations were kept. In that phase, five moulds were tested. The relatively marginal performance of mould M4 led to the discontinuation of tests of that mould and, consequently, only the following four moulds were tested in this phase: M1, M2, M3, and M5.

Mould M1 is the simplest arrangement without any flow guidance or benching at the junction. Although this type would be rarely used in practice, it was included here as an extreme case which would cause the greatest head loss.

Mould M2 was obtained by providing a semicircular channel for the through line and a similar channel for the lateral, except the lateral channel follows a 90° segment of a circle (the radius equals half the manhole width) in the plan (see Fig. 9 - Junction of a Main with a Perpendicular Lateral). This type of benching is fairly common in municipal practice and should provide some guidance to the flows merging at the junction and maintain a good access to the manhole.

Mould M3 represents an improved variation of mould M2 which was obtained by extending the side walls to the pipe crown and placing the horizontal benches at that level. Such an arrangement should provide more flow guidance and, therefore, lower head losses.

Mould M5 was proposed to further lower head losses at the junction. It is in principle mould M3 with expanded channel dimensions at the junction. The alignment between the normal size sewer pipes and the expanded junction channels is obtained by means of eccentric pipe expanders/reducers of standard design. By expanding the flow cross-section at the junction, the flow velocities and the corresponding head losses are reduced. This mould produced the lowest head losses in the earlier phase of this study.

Although the above junction moulds do not exhaust all the possible geometries, they represent a wide range of conditions from the worst case (M1) to the best practical case (M5). Experimental results obtained for these moulds can then be used to make inferences for other designs.

Both round-base and square-base manholes were tested. The round-base manhole was obtained by placing an insert into the square-base manhole.

Details of experimental procedures were given earlier in Chapter 3. A sketch of the experimental apparatus is shown in Fig. 10 - Experimental Apparatus (Phase 2).

4.2.3 Pressurized Flow Results

The head losses in pressurized flow were investigated most extensively, because such conditions are of primary interest to sewer designers. In all experiments, significant head losses were observed at the junction. Although the pressure fluctuations in pipe sections were relatively small, large agitation of the water surface at the junction manhole was observed. Under some conditions, a surface roller (similar to that occurring in a hydraulic jump) developed at the junction. Large eddies and vortices generated at the junction affected the flow conditions in the downstream pipe. Such flow conditions were characterized by secondary helical currents. Effects of various experimental factors are discussed below.

For general discussion of results, it was found convenient to process the head loss data by establishing mean values of the loss coefficients for the range of Q_ℓ/Q_o from 0.0 to 1.0. The procedures used are further described below.

For individual experimental runs, the loss coefficients K_{pm} and $K_{p\ell}$ were plotted in graphs versus the relative lateral discharge. Such plots were then approximated by regression curves (quadratic polynomials) to smooth experimental data and to facilitate further processing, as shown in Figs. 11 - Pressure Head Loss Coefficient vs. Q_ℓ/Q_o (K_{pm}, Phase 2), and 12 - Pressure Head Loss

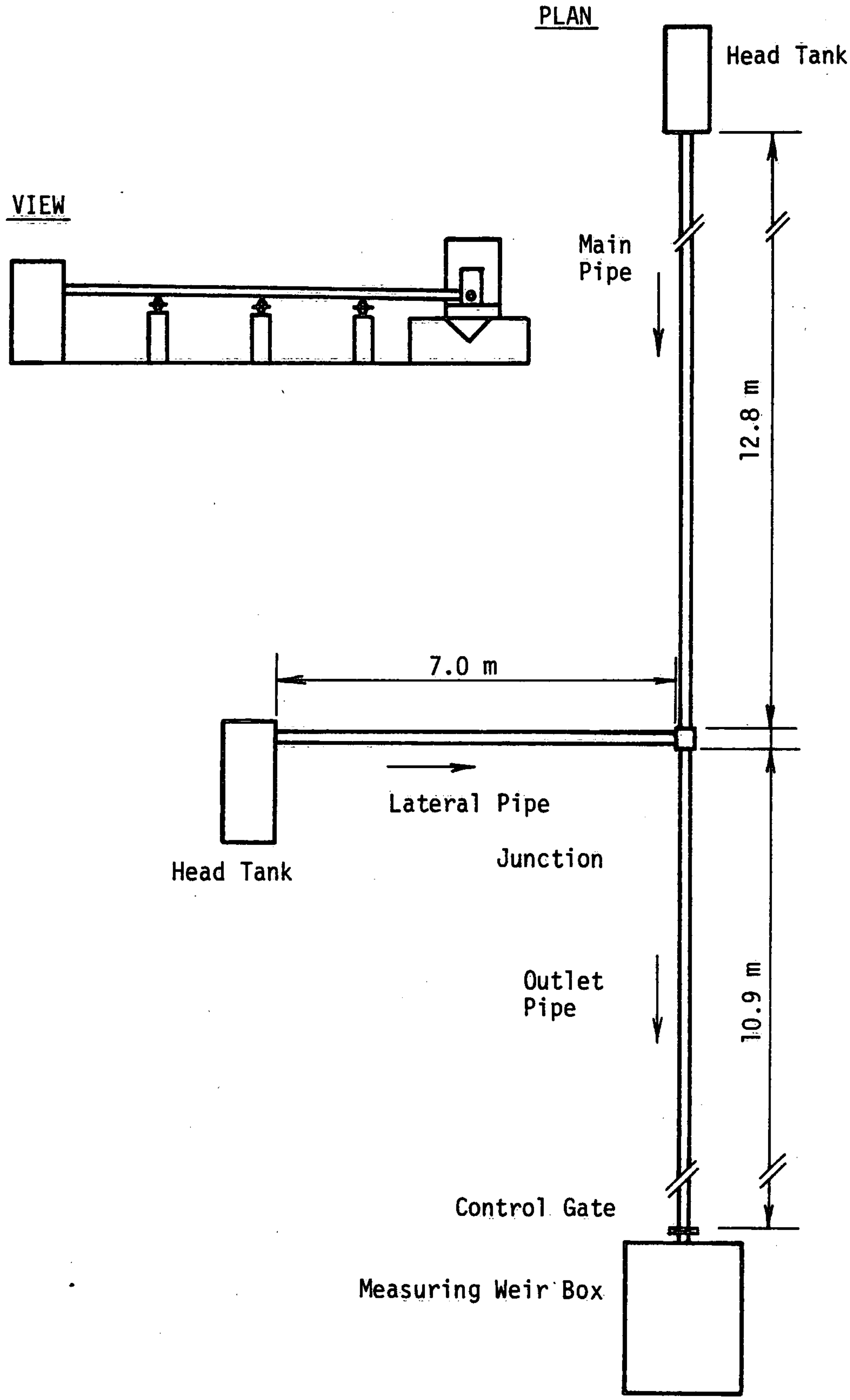


Fig.10. Experimental Apparatus (Phase 2)

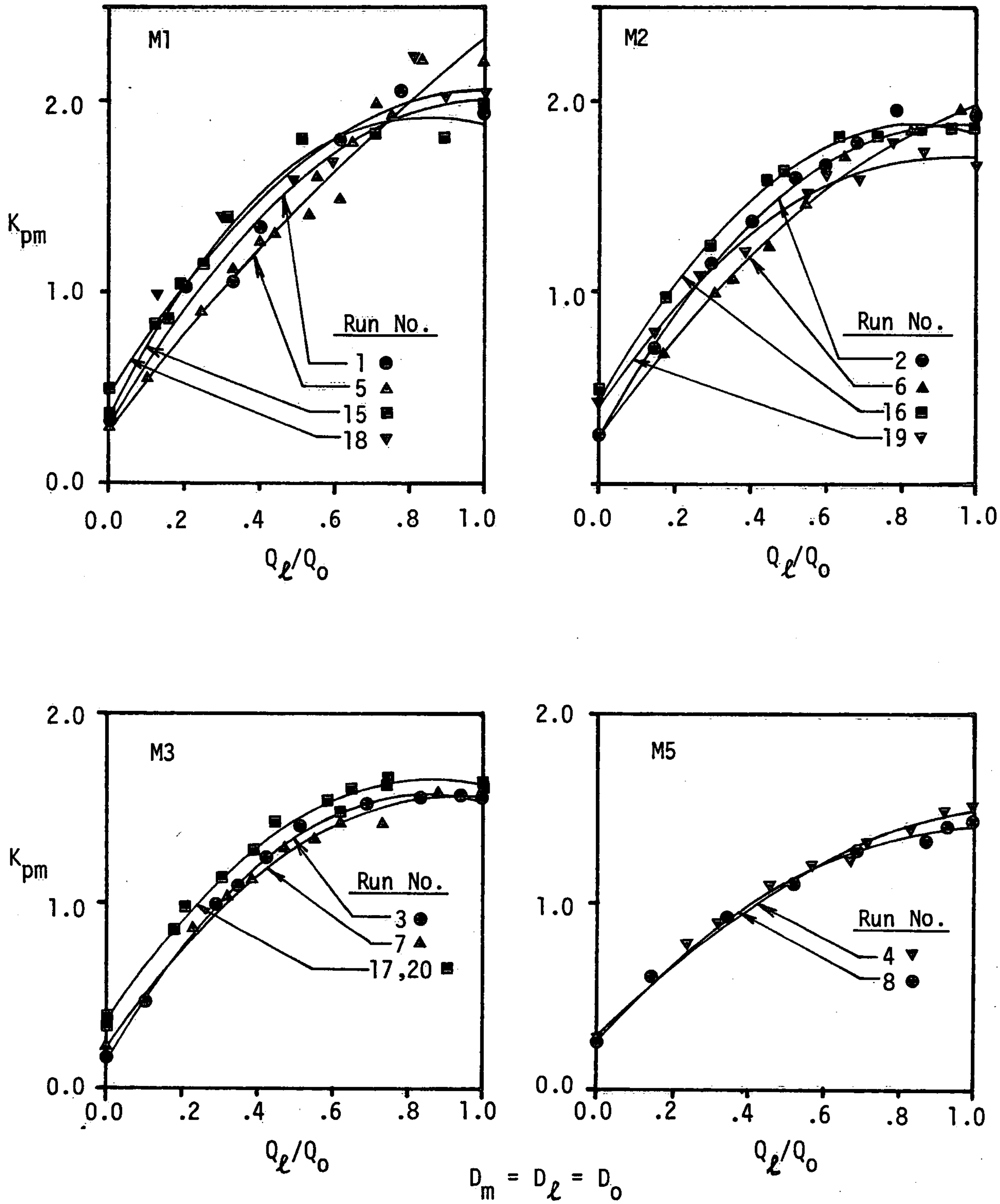


Fig.11. Pressure Head Loss Coefficient vs. Q_ℓ/Q_o (K_{pm}, Phase 2)

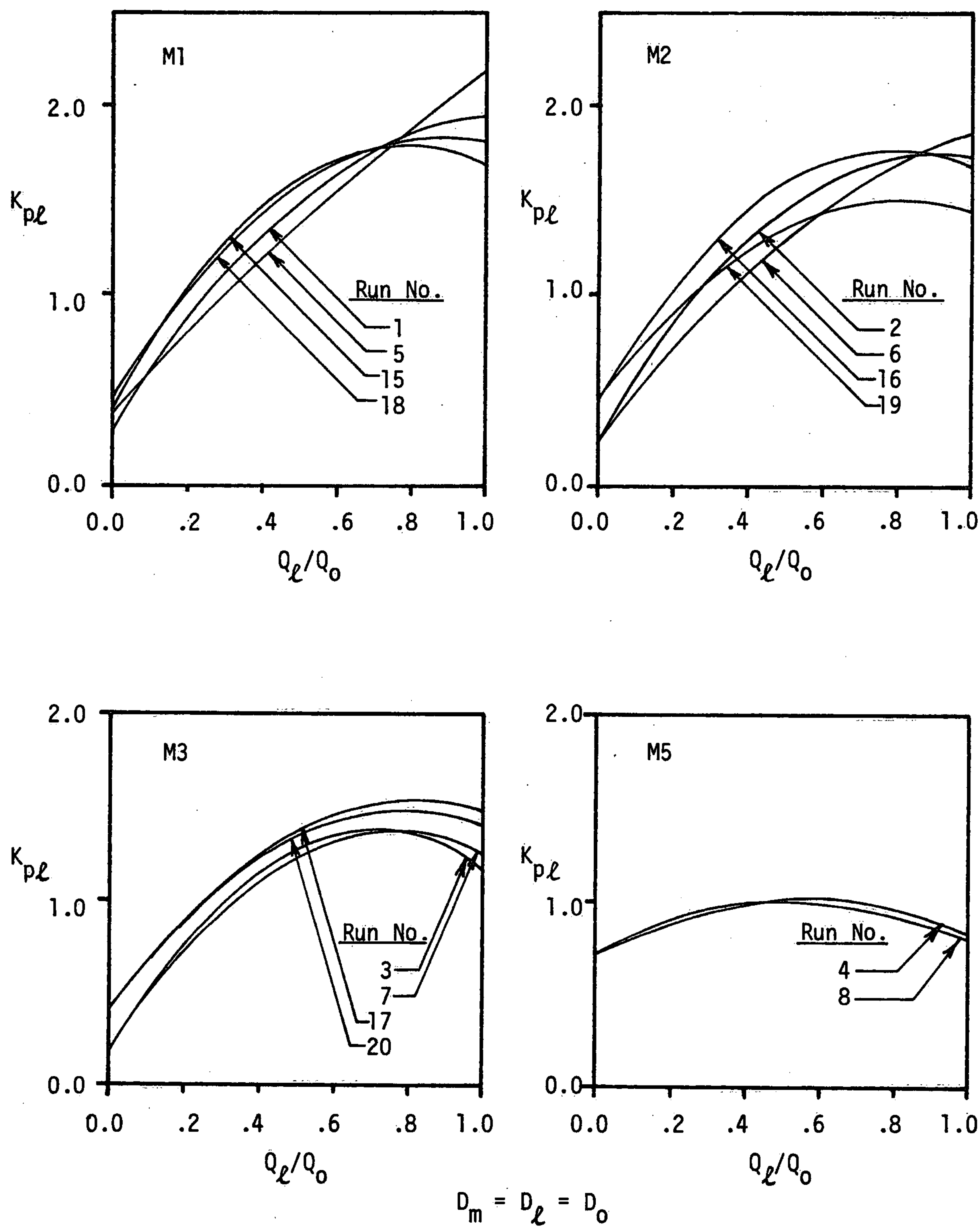


Fig.12. Pressure Head Loss Coefficient vs. Q_ℓ/Q_o ($K_{p\ell}$, Phase 2)

Coefficient vs. Q_ℓ/Q_o ($K_{p\ell}$, Phase 2). Very high values of the regression coefficient were achieved; r^2 typically varied from 0.96 to 0.99, with the exception of the mould M5.

For the overall evaluation of individual runs, the five coefficients derived below were introduced.

A power loss coefficient was proposed by Lindvall (9). This coefficient reflects the total loss of power at the junction for all branches. The total power loss at the junction can be expressed as:

$$L_p = \rho g \left(E_m Q_m + E_\ell Q_\ell - E_o Q_o\right) \tag{18}$$

where ρ is the water density, E is the energy gradient at the junction, and subscripts m, ℓ, and o refer to individual branches. The power loss coefficient C_p is then defined as the ratio of the total power loss to the power of the flow leaving the junction (i.e., $\rho g E_o Q_o$):

$$C_p = \frac{L_p}{\rho g E_o Q_o} = \frac{\rho g E_m Q_m}{\rho g E_o Q_o} + \frac{\rho g E_\ell Q_\ell}{\rho g E_o Q_o} - 1 \tag{19}$$

If further follows that $E_m = P_m + \dfrac{V_m^2}{2g}$, $E_\ell = P_\ell + \dfrac{V_\ell^2}{2g}$, and $E_o = \dfrac{V_o^2}{2g}$.

After substitution, the following expression is obtained:

$$C_p = (1 - x)\left[K_{pm} - (1 - x)^2 \left(\frac{D_o}{D_m}\right)^4\right] + x\left[K_{p\ell} - x^2 \left(\frac{D_o}{D_\ell}\right)^4\right] - 1 \tag{20}$$

where $x = Q_\ell/Q_o$. The mean power loss coefficient was then defined as:

$$\bar{C}_p = \int_0^1 C_p dx \tag{21}$$

and evaluated for individual runs. Analogously, the following mean loss coefficients were also defined:

$$\bar{K}_m = \int_0^1 K_m dx \qquad \bar{K}_\ell = \int_0^1 K_\ell dx \tag{22}$$

$$\bar{K}_{pm} = \int_0^1 K_{pm} dx \qquad \bar{K}_{p\ell} = \int_0^1 K_{p\ell} dx \qquad (23)$$

All five coefficients defined by eqs. (21) to (23) were determined for all experimental runs and presented in Table 10 - Junction of a Main with a Perpendicular Lateral: Mean Power, Head and Pressure Loss Coefficients.

TABLE 10. JUNCTIONS OF A MAIN WITH A PERPENDICULAR LATERAL - MEAN POWER, HEAD AND PRESSURE LOSS COEFFICIENTS

Run No.	$\frac{D_{mh}}{D_o}$	$\frac{D_m}{D_o}$	$\frac{D_\ell}{D_o}$	$\bar{C}_p$	$\bar{K}_m$	$\bar{K}_\ell$	$\bar{K}_{pm}$	$\bar{K}_{p\ell}$
1	2.3	1.0	1.0	0.90	0.77	0.71	1.43	1.37
2	2.3	1.0	1.0	0.83	0.71	0.64	1.38	1.31
3	2.3	1.0	1.0	0.59	0.50	0.41	1.17	1.07
4	2.3	1.0	1.0	0.39	0.36	0.26	1.02	0.93
5	2.3	1.0	1.0	0.85	0.73	0.67	1.40	1.34
6	2.3	1.0	1.0	0.74	0.62	0.56	1.29	1.22
7	2.3	1.0	1.0	0.58	0.48	0.40	1.15	1.06
8	2.3	1.0	1.0	0.37	0.34	0.25	1.00	0.92
15	4.6	1.0	1.0	0.95	0.84	0.77	1.50	1.44
16	4.6	1.0	1.0	0.94	0.81	0.76	1.48	1.43
17	4.6	1.0	1.0	0.74	0.61	0.56	1.28	1.23
18	4.6	1.0	1.0	0.97	0.87	0.78	1.54	1.44
19	4.6	1.0	1.0	0.75	0.66	0.56	1.33	1.23
20	4.6	1.0	1.0	0.72	0.62	0.53	1.29	1.20
21	2.3	1.0	0.5	4.74	1.38	5.37	2.04	1.04
22	2.3	1.0	0.5	4.80	1.20	5.73	1.86	1.39
23	2.3	1.0	0.5	3.60	0.93	4.20	1.60	-0.14
24	2.3	1.0	0.5	2.61	0.40	3.19	1.07	-1.15
Open-Channel Flow								
9,13	2.3	1.0	1.0	-	0.23	0.06	-	-
10,14	2.3	1.0	1.0	-	0.11	0.08	-	-
11	2.3	1.0	1.0	-	0.10	0.12	-	-
12	2.3	1.0	1.0	-	0.02	0.09	-	-

It should be further noted that the energy and pressure loss coefficients are related by the following simple expressions which follow from basic definitions:

$$K_m = K_{pm} - 1 + (1 - x)^2 \left(\frac{D_o}{D_m}\right)^4 \quad (24)$$

$$K_\ell = K_{p\ell} - 1 + x^2 \left(\frac{D_o}{D_m}\right)^4 \quad (25)$$

Further discussion of individual experimental factors follows.

Lateral Inflow (Q_ℓ/Q_o)

The earlier presented plots of head and pressure losses indicate that these losses increase with increasing Q_ℓ/Q_o. For $Q_\ell/Q_o = 0$ (no lateral inflow), the head loss for mould M1 (no benching) is similar to that for straight-flow-through manholes (7,10). For other moulds, the values reported here were somewhat higher than those corresponding to straight-flow-through manholes, because the presence of the lateral inflow channel caused some flow disturbances at the junction. The other extreme was found for $Q_\ell/Q_o = 1$ (all flow through the lateral). For mould M1, this case is similar to that of a manhole with a 90° bend. For other moulds, the presence of the main channel slightly alters the flow through the junction and the resulting loss. It was also noticed that the water level fluctuated at the junction and these fluctuations were reflected in pressure fluctuations in the branch without any discharge and possibly in head losses as well.

The plots of K versus Q_ℓ/Q_o had a characteristic shape. K increased sharply with an increasing Q_ℓ/Q_o and attained large values, close to the maximum, for $Q_\ell/Q_o = 0.7$ to 0.8. The highest losses were typically found for $Q_\ell/Q_o = 1.0$.

Relative Manhole Size (b/D_o, or D_{mh}/D_o)

Although the relative manhole size may affect individual values of loss coefficients, the differences found for paired (e.g., for b/D_o or D_{mh}/D_o = 2.3 and 4.6) mean coefficients were rather small, typically less than 4%. Thus, although the higher b/D_o (D_{mh}/D_o) values led to somewhat higher power and energy losses, such increases were insignificant.

Relative Size of the Lateral (D_ℓ/D_o; in all runs, $D_m = D_o$)

The effects of the relative size of the lateral were studied for various moulds in the last four runs. In those runs, the small pipe (D = 3 in = 75 mm) was used as the lateral and the large pipe (D = 6 in = 152 mm) was used as the main and outlet.

In experiments with the small lateral and large main and outlet, for identical discharges, the momentum of the lateral flow is greater than in the case of a constant pipe diameter throughout the installation. Thus the lateral flow may have tendencies to disrupt more the main stream passing through the junction. The recovery of the energy of the lateral flow passing through the junction may be also lower. Thus higher head losses can be expected in this case.

Comparisons of head loss coefficients indicate that the head losses in the main pipe for the small lateral (and large outlet and main) exceeded those for the runs with the same-size pipes by 40% to 60%. This confirms the expected behaviour of such junctions as discussed above. When comparing various moulds, the results were similar as for the earlier runs - the losses decreased from mould M1 to M5.

For the lateral pipe, very large head loss coefficients were found, up to $K_\ell = 16.0$. Note, however, that such large values follow from the way the head loss coefficients were expressed here, as a fraction of the velocity head in the outlet. Because the outlet diameter is twice the lateral diameter, the corresponding ratio of velocities is 1:4 and the ratio of velocity heads ($V^2/2g$) is 1:16. Thus, the head loss coefficient of 16, based on the outlet head, corresponds to the value of 1.0 when based on the lateral head. The lateral head loss increased with an increasing ratio Q_ℓ/Q_o and reached the maximum for zero main pipe flow. Moulds M1 and M2 performed quite similarly, with M2 even yielding marginally larger values than M1. Lower losses were observed for M3 and M5.

Comparisons of Main Pipe Losses to Lateral Pipe Losses

The mean values of the main and lateral pipe loss coefficients are comparable, except for runs with $D_\ell/D_o < 1$. The main pipe head loss coefficients were about 14% larger than those for the lateral pipe. In case of the pressure loss coefficient, the corresponding difference was only 6%.

In runs with the small lateral ($D_\ell/D_o = 0.5$), energy head losses in the lateral greatly exceeded those in the main. On the other hand, pressure change coefficients for the main exceeded those for the lateral.

Manhole Benching (Moulds M1 to M5)

The effect of the manhole benching on mean losses at the junction was rather pronounced. As expected, the highest losses were observed at junctions without benching (mould M1). Such losses were reduced by about 12% for mould M2, 31% for mould M3, and almost 60% for mould M5.

Manhole Base Shape

The base shape may influence the losses primarily by contributing to the formation of certain flow patterns inside the junction. A quick evaluation of the base shape effects was obtained by comparing paired results (i.e., for round- and square-base) from Table 10 - Junction of a Main with a Perpendicular Lateral: Mean Power, Head and Pressure Loss Coefficients. The average deviations between paired sets of data were rather small and, therefore, considered insignificant.

4.2.4 Open-Channel Flow Results

The scope of experiments with open-channel flow was rather limited - six runs altogether. All these runs were made for the larger pipe (6 in, 152 mm), both the square- and round-base manholes, and for two to four moulds. Note that in the case of the round-base manhole, mould M3 and M5 yield identical geometries as the square-base manhole and, consequently, there was no need to repeat the testing of such installations.

The results for open-channel flow are listed in Table 10 - Junction of a Main with a Perpendicular Lateral: Mean Power, Head and Pressure Loss Coefficients. Head loss coefficients for the main and lateral are also plotted in Fig. 13 - Head Loss Coefficient K_m vs. Q_ℓ/Q_o - Open-Channel Flow (Phase 2), and Fig. 14 - Head Loss Coefficient K_ℓ vs. Q_ℓ/Q_o - Open-Channel Flow (Phase 2). In comparison to the pressurized flow results, it is obvious that the losses in the open-channel flow are significantly smaller. This follows from smaller changes in the channel geometry at the junction, particularly when benchings are used at the junction.

The head loss coefficient for the main pipe exhibited low variations with Q_r. The highest mean coefficient value was found for mould M1 - $K_m = 0.23$. This value was substantially reduced for mould M2 - $K_m = 0.11$. Further reductions were observed for mould M3 ($K_m = 0.10$) and M5 ($K_m = 0.02$).

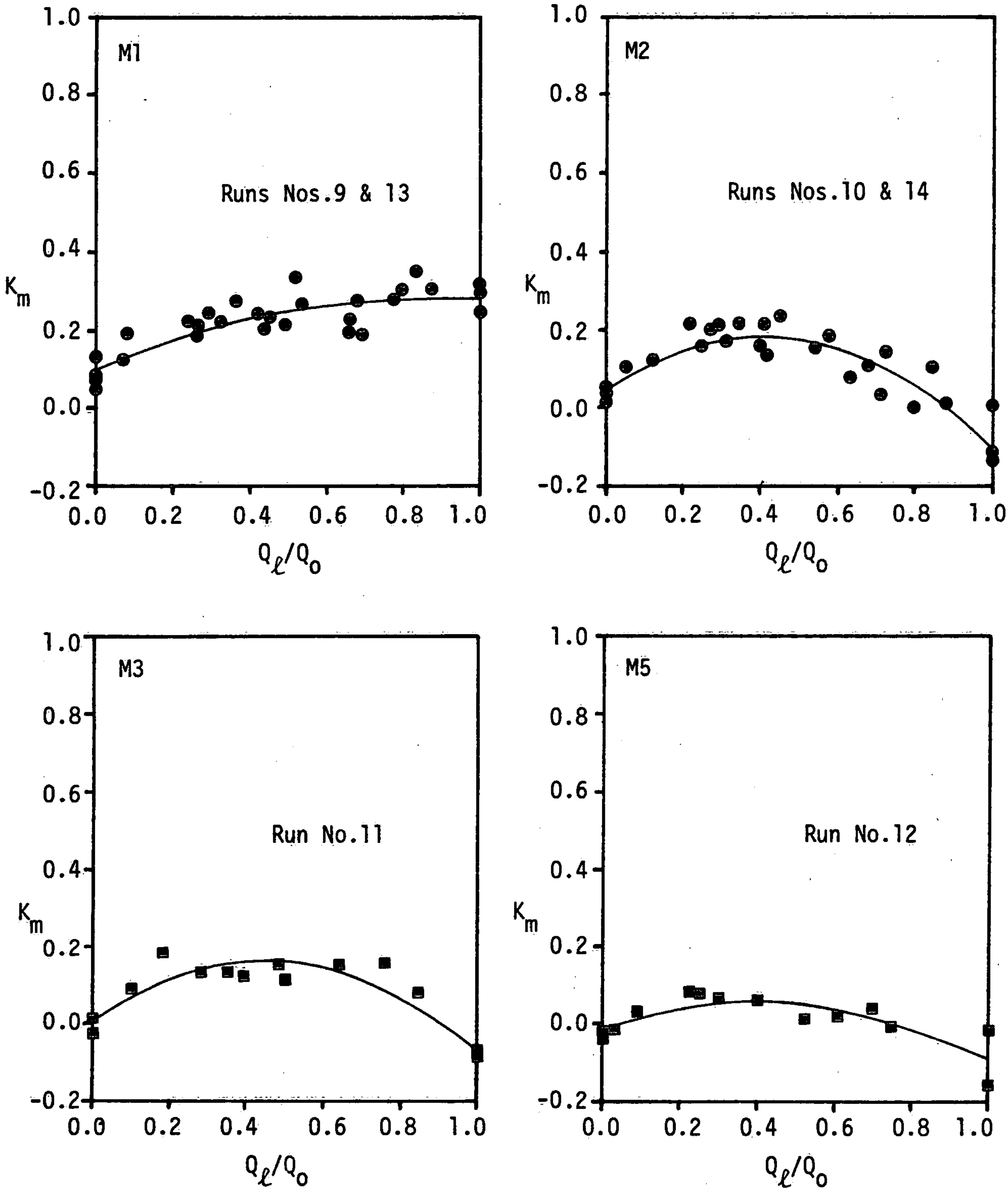


Fig.13. Head Loss Coefficient K_m vs. Q_ℓ/Q_o - Open-Channel Flow(Phase 2)

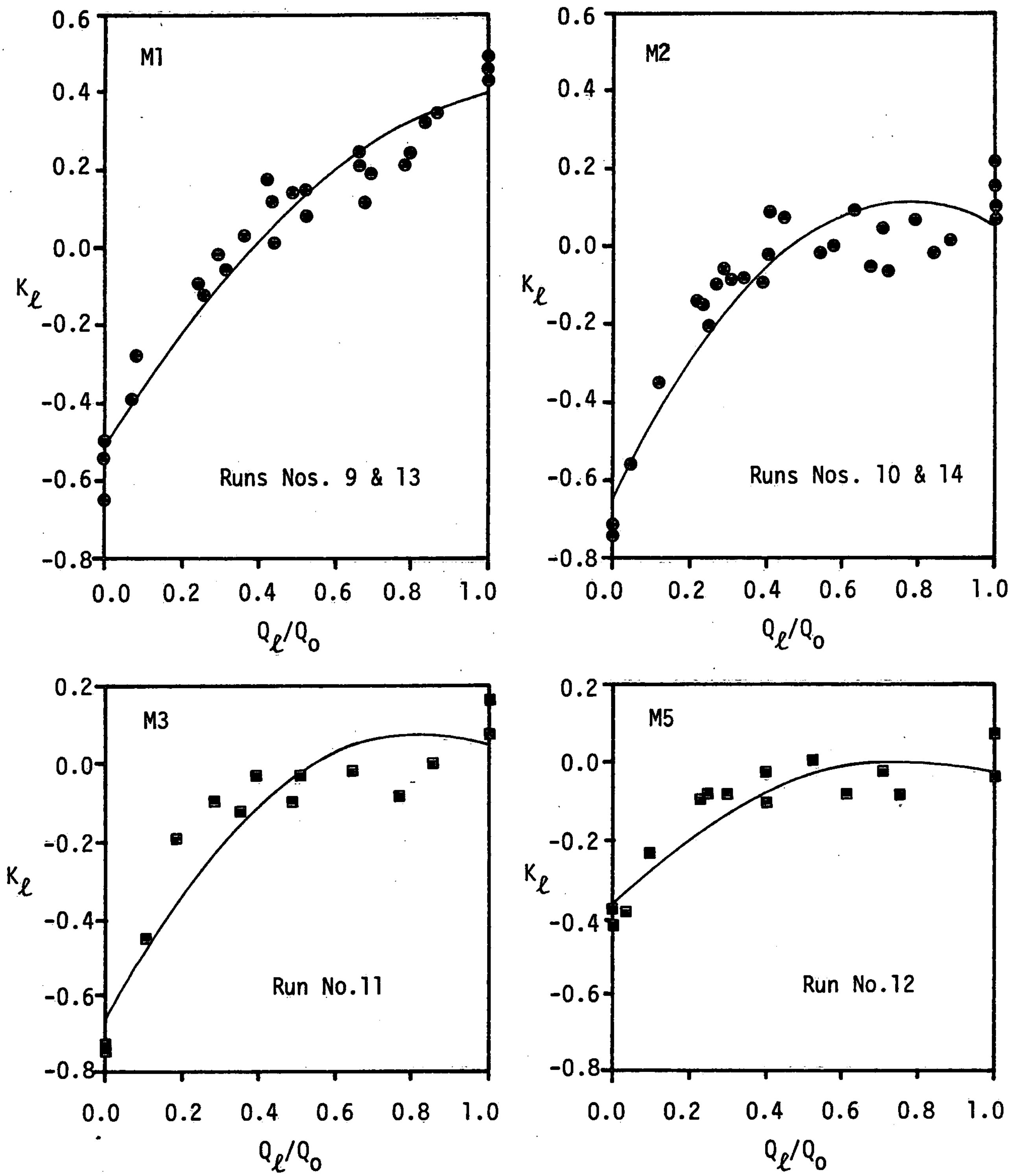


Fig.14. Head Loss Coefficient K_ℓ vs. Q_ℓ/Q_o - Open Channel Flow(Phase 2)

For the lateral pipe, the head loss coefficients varied more sharply. For low lateral inflows ($Q_r < 0.5$), the head loss coefficient attained negative values. It then increased sharply for higher lateral inflows. For mould M1, the highest coefficient value was about 0.4. The corresponding value for mould M2 was about 0.14, and 0.075 for mould M3. For mould M5, the head loss coefficient barely exceeded zero.

4.2.5 Sulphide Gas Releases

The probability of sulphide gas releases at junction manholes in combined or sanitary sewers was evaluated qualitatively assuming that such releases result form high turbulence and agitation at the junction. Using the same approach as in section 4.1.5, various junction designs were evaluated as shown in Table 11 - Evaluations of Junctions of a Main with a Lateral for Suphide Gas Releases.

TABLE 11. EVALUATION OF JUNCTIONS OF A MAIN WITH A LATERAL FOR SULPHIDE GAS RELEASES

Mould (Both square and round manholes)	Turbulence Rating	Susceptibility to Sulphide Gas Release
M1	2	medium
M2	2	medium
M3	1	low
M5	1	low

It was further noticed that turbulence at the junction was affected by the depth of surcharge and the relative lateral inflow (Q_ℓ/Q_o). More quiescent conditions were found for greater surcharge ($S/D_o \geq 2$). For low surcharge or $Q_\ell/Q_o = 1$, higher turbulence was observed and the susceptibility to gas releases, listed above, would be increased by one category.

4.2.6 Design Data

The plots of experimental data decribed earlier were approximated by regression equations which were then used to produce tables of loss coefficients for various relative discharges and junction geometries. Detailed tables for various experimental runs are given in the Appendix. Only the summary tables (i.e., with one value for each relative discharge and the mould) are presented here.

Table 12 - Pressure Change and Head Loss Coefficients for Junctions of a Main with a Lateral, lists data for $D_\ell = D_o$ (= D_m) and four different moulds. Table 13 - Pressure Change and Head Loss Coefficients for Junctions of a Main with a Lateral, lists data for $D_\ell = D_o/2$ and four different moulds. Variations in coefficients caused by the relative manhole size (b/D_o, or D_{mh}/D_o) are reflected in tables in the Appendix.

TABLE 12. PRESSURE CHANGE AND HEAD LOSS COEFFICIENTS FOR JUNCTIONS OF A MAIN WITH A LATERAL ($D_\ell = D_o = D_m$)

Pressure Change Coefficients

Q_ℓ/Q_o	K_{pm}				$K_{p\ell}$			
	M1	M2	M3	M5	M1	M2	M3	M5
0.0	0.4	0.3	0.3	0.3	0.4	0.4	0.3	0.7
0.1	0.7	0.6	0.6	0.5	0.7	0.6	0.6	0.8
0.2	0.9	0.9	0.8	0.7	0.9	0.9	0.8	0.9
0.3	1.2	1.1	1.0	0.8	1.2	1.1	1.0	0.9
0.4	1.4	1.3	1.2	1.0	1.4	1.3	1.2	1.0
0.5	1.6	1.5	1.4	1.1	1.6	1.4	1.3	1.0
0.6	1.8	1.6	1.5	1.2	1.8	1.6	1.4	1.0
0.7	1.9	1.7	1.6	1.3	1.9	1.6	1.4	1.0
0.8	2.0	1.8	1.6	1.4	2.0	1.7	1.4	1.0
0.9	2.0	1.9	1.6	1.4	2.0	1.7	1.4	0.9
1.0	2.1	1.9	1.6	1.4	2.1	1.7	1.3	0.8

Energy Head Loss Coefficients

Q_ℓ/Q_o	K_m				K_ℓ			
	M1	M2	M3	M5	M1	M2	M3	M5
0.0	0.4	0.3	0.3	0.3	-0.6	-0.7	-0.7	-0.3
0.1	0.5	0.4	0.4	0.3	-0.3	-0.4	-0.4	-0.2
0.2	0.6	0.5	0.5	0.3	0.0	-0.1	-0.1	-0.1
0.3	0.7	0.6	0.5	0.3	0.3	0.2	0.1	0.0
0.4	0.8	0.7	0.6	0.3	0.5	0.4	0.3	0.2
0.5	0.8	0.8	0.6	0.3	0.8	0.7	0.6	0.3
0.6	0.9	0.8	0.6	0.4	1.0	0.9	0.7	0.4
0.7	1.0	0.8	0.6	0.4	1.3	1.1	0.9	0.5
0.8	1.0	0.9	0.6	0.4	1.5	1.3	1.1	0.6
0.9	1.0	0.9	0.6	0.4	1.7	1.5	1.2	0.7
1.0	1.1	0.9	0.6	0.4	1.9	1.7	1.3	0.8

TABLE 13. PRESSURE CHANGE AND HEAD LOSS COEFFICIENTS FOR JUNCTIONS OF A MAIN WITH A LATERAL ($D_\ell = 0.5\ D_o = 0.5\ D_m$)

	Pressure Change Coefficients							
	K_{pm}				$K_{p\ell}$			
Q_ℓ / Q_o	M1	M2	M3	M5	M1	M2	M3	M5
0.0	0.7	0.2	0.4	0.1	0.2	0.1	0.4	0.8
0.1	1.1	0.7	0.7	0.4	0.4	0.6	0.6	0.8
0.2	1.4	1.2	1.1	0.7	0.6	1.0	0.7	0.6
0.3	1.7	1.5	1.3	0.9	0.8	1.3	0.6	0.3
0.4	2.0	1.9	1.6	1.1	1.0	1.5	0.5	-0.1
0.5	2.2	2.1	1.8	1.2	1.1	1.7	0.3	-0.7
0.6	2.4	2.3	1.9	1.4	1.3	1.8	0.0	-1.3
0.7	2.5	2.5	2.0	1.4	1.4	1.8	-0.5	-2.1
0.8	2.6	2.5	2.1	1.5	1.4	1.8	-1.0	-2.9
0.9	2.7	2.5	2.2	1.5	1.5	1.6	-1.6	-3.9
1.0	2.7	2.5	2.2	1.4	1.5	1.4	-2.4	-5.0

	Energy Head Loss Coefficients							
	K_m				K_ℓ			
Q_ℓ / Q_o	M1	M2	M3	M5	M1	M2	M3	M5
0.0	0.7	0.2	0.4	0.1	-0.8	-0.9	-0.6	-0.1
0.1	0.9	0.5	0.5	0.2	-0.6	-0.4	-0.4	-0.2
0.2	1.1	0.8	0.7	0.3	-0.3	0.0	-0.3	-0.4
0.3	1.2	1.0	0.8	0.4	-0.1	0.4	-0.3	-0.7
0.4	1.4	1.2	0.9	0.4	0.1	0.7	-0.3	-1.0
0.5	1.5	1.4	1.0	0.5	0.4	1.0	-0.5	-1.4
0.6	1.6	1.5	1.1	0.5	0.6	1.2	-0.7	-2.0
0.7	1.6	1.6	1.1	0.5	0.8	1.3	-1.0	-2.6
0.8	1.7	1.6	1.2	0.5	1.1	1.4	-1.4	-3.3
0.9	1.7	1.5	1.2	0.5	1.3	1.4	-1.8	-4.1
1.0	1.7	1.5	1.2	0.4	1.5	1.4	-2.4	-5.0

For open-channel flow junctions, some guidance can be obtained from Table 10 - Junctions of a Main with a Perpendicular Lateral: Mean Power, Head and Pressure Loss Coefficients, Fig. 13 - Head Loss Coefficient K_m vs. Q_ℓ/Q_o - Open-Channel Flow, and Fig. 14 - Head Loss Coefficient K_ℓ vs. Q_ℓ/Q_o - Open-Channel Flow.

4.2.7 Design Examples

For illustration of the design data given in the preceding section, several simple examples are presented below.

Example No. 1

Calculate pressure and head losses at a surcharged junction of a main with a perpendicular lateral for the following conditions:

Sewer diameters - $D_m = D_\ell = D_o = 0.61$ m (24 in)

Discharges - $Q_m = 0.438$ m^3/s (15.4 cfs),
$Q_\ell = 0.146$ m^3/s (5.2 cfs)
$Q_o = 0.584$ m^3/s (20.6 cfs)

Manhole - a round base manhole, 1.22 m (4 ft) in diameter, without any benching.

Step 1 - Calculate the outlet velocity head

$$H_o = V^2/2\,g = \left(\frac{Q}{A_o}\right)^2/2\,g$$

where $A_o = \pi D_o^2/4 = \pi \times 0.61^2/4 = 0.292$ m^2

$$H_o = \left(\frac{0.584}{0.292}\right)^2/2 \times 9.81 = 0.204 \text{ m (0.67 ft)}$$

Step 2 - Determine the loss coefficients. For $Q_r = Q_\ell/Q_o = 0.25$ and mould M1, interpolate from Table 12 the following coefficient values:

$K_{pm} = 1.05$ $\quad K_{p\ell} = 1.05$

$K_m = 0.65$ $\quad K_\ell = 0.15$

Step 3 - Calculate the losses as

$\Delta P_m = K_{pm}\,H_o = 1.05 \times 0.204 = 0.214$ m (0.70 ft)

$\Delta P_\ell = K_{p\ell}\,H_o = 1.05 \times 0.204 = 0.214$ m (0.70 ft)

$\Delta E_m = K_m\,H_o = 0.65 \times 0.204 = 0.133$ m (0.44 ft)

$\Delta E_\ell = K_\ell\,H_o = 0.15 \times 0.204 = 0.031$ m (0.10 ft)

In terms of pressure changes, both the main and lateral experience the same pressure drop of 0.214 m (0.70 ft). For energy grade lines, the loss in the main is much larger (0.133 m, or 0.44 ft) than that in the lateral (0.031 m or 0.10 ft).

Example No. 2

Establish pressure and head losses for the same data as in Example 1, except for a smaller lateral pipe diameter - D_ℓ = 0.305 m (12 in).

Step 1 - is the same as in Example 1.

Step 2 - Determine the loss coefficients. From Table 13, interpolate for Q_r = 0.25 and mould M1 the following coefficient values:

K_{pm} = 1.55 $K_{p\ell}$ = 0.70

K_m = 1.15 K_ℓ = -0.20

Step 3 - Calculate the losses. For the above loss coefficients, the losses are calculated as follows:

$\Delta P_m = K_{pm} H_o =$ 1.55 x 0.204 = 0.316 m (1.04 ft)

$\Delta P_\ell = K_{p\ell} H_o =$ 0.70 x 0.204 = 0.143 m (0.47 ft)

$\Delta E_m = K_m H_o =$ 1.15 x 0.204 = 0.235 m (0.77 ft)

$\Delta E_\ell = K_\ell H_o =$ -0.20 x 0.204 = -0.041 m (0.13 ft)

The pressure and head losses in the main, 0.316 m (1.04 ft) and 0.235 m (0.77 ft), respectively, are greater than in Example 1. On the other hand, the losses in the lateral are smaller. Note that energy gains (e.g., E_ℓ = -0.041 m) are neglected in practical design.

Example No. 3

Determine the head loss at the junction from Example 1 for a subcritical open-channel flow. The flow data are as follows:

Q_m = 0.280 m^3/s (9.9 cfs), Q_ℓ = 0.120 m^3/s (4.2 cfs), Q_o = 0.400 m^3/s (14.1 cfs), and the depth of flow in the outlet is h = 0.55 m (1.8 ft).

Step 1 - Calculate the free flow velocity head for the outlet as

$$H_o = \left(\frac{Q_o}{A_o}\right)^2 /2\,g = \left(\frac{0.400}{0.277}\right)^2 /2 \times 9.81 = 0.107 \text{ m } (0.35 \text{ ft})$$

Step 2 - For $Q_r = Q_\ell/Q_o = 0.120/0.400 = 0.3$ and mould M1, determine the head loss coefficients from Figs. 13 and 14 as

$K_m = 0.2$ $\qquad$ $K_\ell = -0.1$

Step 3 - Calculate the head losses as

$$\Delta E_m = K_m \times H_o = 0.2 \times 0.107 = 0.021 \text{ m } (0.07 \text{ ft})$$

$$\Delta E_\ell = K_\ell \times H_o = -0.1 \times 0.107 = -0.011 \text{ m } (0.04 \text{ ft})$$

The head loss in the main is 0.021 m (0.07 ft). The negative loss in the lateral would be neglected.

4.2.8 Summary

The principal findings of the second study phase which dealt with head and pressure losses at junctions of a main with a perpendicular lateral are summarized in four points below.

(1) Head and pressure losses at junctions of a main with a perpendicular lateral are affected by both the junction geometry and the relative discharge Q_r, defined as $Q_r = Q_\ell/Q_o$. Generally, the losses increased with an increasing Q_r.

(2) Among the junction geometry parameters, the benching (moulds) had the most pronounced effect on the head loss, followed by the relative lateral size, the relative manhole width, and the base shape. The lowest head loss coefficients were found for mould M5, followed by municipal designs described as moulds M3 and M2. The arrangement without any benching, mould

M1, produced by far the highest loss coefficients. The small lateral pipe ($D_\ell = 0.5\ D_o$) contributed to higher head losses, by 40% to 60%. The wider manhole produced somewhat higher losses, by about 16%. This was caused by larger changes in the flow cross-sections at the junction. Although the square-base manholes produced slightly higher losses than the round-base manholes, such an increase (8%) was hardly significant in view of experimental uncertainties.

(3) Noticeable differences between head loss coefficients for the main and lateral pipes were observed. Although both coefficients generally increased with an increasing Q_r, the increases in the lateral coefficient were much larger. For very low lateral discharges, the flow from the lateral pipe experienced an energy gain rather than loss.

(4) Head losses for the open-channel flow conditions were much lower than those in the pressurized flow. In fact, the highest observed head loss coefficient was about 0.4 for mould M1, as compared to the maximum coefficient of 2.0 for the pressurized flow.

4.3 Junctions of Two Opposed Laterals

The junctions of two opposed laterals with a single outlet were studied in the last phase of this study (13). To a large extent, the layout of such junctions is similar to that of the junctions described in the preceding section.

4.3.1 Previous Research

The literature survey revealed only one reference dealing with junctions with two opposed laterals. This was the Sangster et al. report (15) which dealt with junctions with two opposed laterals of various diameters and in-line and off-line alignments.

The main study findings can be summarized as follows:

a) The curves of the pressure change coefficients $K_{p\ell 1}$ and $K_{p\ell 2}$ versus the discharge ratio $Q_{lateral}/Q_{outlet}$ were symmetrical with respect to the line $Q_\ell/Q_o = 0.5$.

b) K_p coefficients for a particular lateral seemed to be fairly constant, for a certain range of Q_ℓ/Q_o, as long as the flow in this lateral exceeded that in the opposed lateral. Thus the coefficient for a particular lateral flow was controlled more by the flow in the opposed lateral than by the flow in the lateral concerned.

c) For identical diameters of all three pipes (i.e., both laterals and the outlet), the pressure loss coefficient approached the value of 1.6.

It was further deduced from Sangster et al. data (15) that the lowest losses were found for laterals of equal diameters. All the data reported above were obtained for pressurized flow and no benching at the junction.

4.3.2 Experimental Work

Junctions of two opposed laterals are very similar to those with a main and a lateral, except for flow routing through the junction and the benching design. Consequently, the functional relationship for K given in the preceding section (eq. (17)) can be used here as well with minor modifications:

$$K = f_9 \left(\frac{Q_{\ell 1}}{Q_o}, \ \frac{b}{D_o} \left(\text{or } \frac{D_{mh}}{D_o}\right), \frac{D_{\ell 1}}{D_o}, \frac{D_{\ell 2}}{D_o}, \text{benching, base shape}\right) \qquad (26)$$

For budgetary reasons, only the case of $D_{\ell_1} = D_{\ell 2} = D_o$ was studied, thus reducing the number of independent variables to five. These remaining five variables were varied in 20 experimental series as shown in Table 14 - Junction of Two Opposed Laterals: Experimental Program and Mean Loss Coefficients, and further described below.

In the experimental program, the following experimental factors were considered:

- Type of flow - pressurized or open-channel flow
- Relative lateral discharge defined as Q_ℓ/Q_o
- Relative manhole size (b/D_o, or D_{mh}/D_o)
- Pipe size - both diameters 75 mm (3 in) and 152 mm (6 in) were used ($D_{\ell 1} = D_{\ell 2} = D_o$)
- Benching at the junction - described as moulds M1, M2, M3 and M5; and,

- Manhole base shape - square or round.

Further explanations and comments follow.

TABLE 14. JUNCTION OF TWO OPPOSED LATERALS - EXPERIMENTAL PROGRAM AND MEAN LOSS COEFFICIENTS

Run No.	Flow Type P = Pressure O = Open Channel	Manhole Base SQ = Square R = Round	Pipe Size* L = Large S = Small	Mould	$\bar{C}_p$	$\bar{K}_\ell$	$\bar{K}_{p\ell}$
1	P	SQ	L	M1	1.44	1.40	2.07
2	P	SQ	L	M2	1.25	1.10	1.77
3	P	SQ	L	M3	0.92	0.82	1.49
4	P	SQ	L	M5	0.65	0.58	1.25
5	P	R	L	M1	1.20	1.15	1.82
6	P	R	L	M2	1.21	1.11	1.77
7	P	R	L	M3	0.98	0.87	1.54
8	P	R	L	M5	0.68	0.62	1.29
9	0	SQ	L	M1	-	-	-
10	0	SQ	L	M2	-	-	-
11	0	SQ	L	M3	-	-	-
12	0	SQ	L	M5	-	-	-
13	0	R	L	M1	-	-	-
14	0	R	L	M2	-	-	-
15	P	SQ	S	M1	1.17	1.13	1.80
16	P	SQ	S	M2	1.09	0.97	1.64
17	P	SQ	S	M3	0.88	0.73	1.40
18	P	R	S	M1	1.18	1.11	1.77
19	P	R	S	M2	1.07	0.93	1.60
20	P	R	S	M3	0.92	0.75	1.42

* In all runs $D_{\ell 1} = D_{\ell 2} = D_o$.

Type of Flow

Experiments were done for both open-channel and pressurized flows, with the emphasis put on the latter. The earlier research indicated that the head losses in open-channel flow are much smaller than in the pressurized flow and the spacing of junctions under free flow conditions may influence the results.

Relative Discharge

The results obtained by Sangster et al. (15) as well as the earlier progress report on a similar junction (13) indicate that the ratio Q_ℓ/Q_o is the main experimental variable controlling head losses in this type of junction manhole. Consequently, the relative discharge $Q_r = Q_{lateral}/Q_{outflow}$, was varied from zero to one in all experimental runs.

Relative Manhole Size

The relative manhole size was described by the ratio of the characteristic manhole cross-sectional dimension, either the diameter or the base width, to the main pipe diameter. Following the findings of the APWA survey and the earlier research phase, two values of this ratio were employed by keeping the same junction manhole (b or D_{mh} = 0.34 m) but using two pipe sizes - 75 mm and 152 mm, respectively (3 and 6 in., respectively). Thus the following two manhole sizes were obtained:

$$\frac{b}{D_o} \text{ or } \frac{D_{mh}}{D_o} = 2.3 \text{ and } 4.6$$

Pipe Size

As mentioned above, two pipe sizes of 75 mm (3 in) and 152 mm (6 in) were used in the experiments to obtain two relative manhole sizes. In all tests, the same pipe size was used throughout the installation.

Benching

Four different benching designs, referred to as moulds, were used in this phase of the study. These four moulds, M1 to M3 and M5, were analogous to those described in the preceding section. Mould M1, which was used in all Sangster et al. (15) tests, represented the case with no benching. Although this type would be rarely used in practice, particularly in the case of a junction with two opposed laterals, it was included here as an extreme reference case which would produce the greatest losses. The remaining moulds provided some guidance for inflows from both laterals.

Mould M2 was obtained by providing semicircular channels, for both laterals, following 90° segments of a circle (the radius equals half the manhole width) in the plan (see Fig. 15 - Junction of

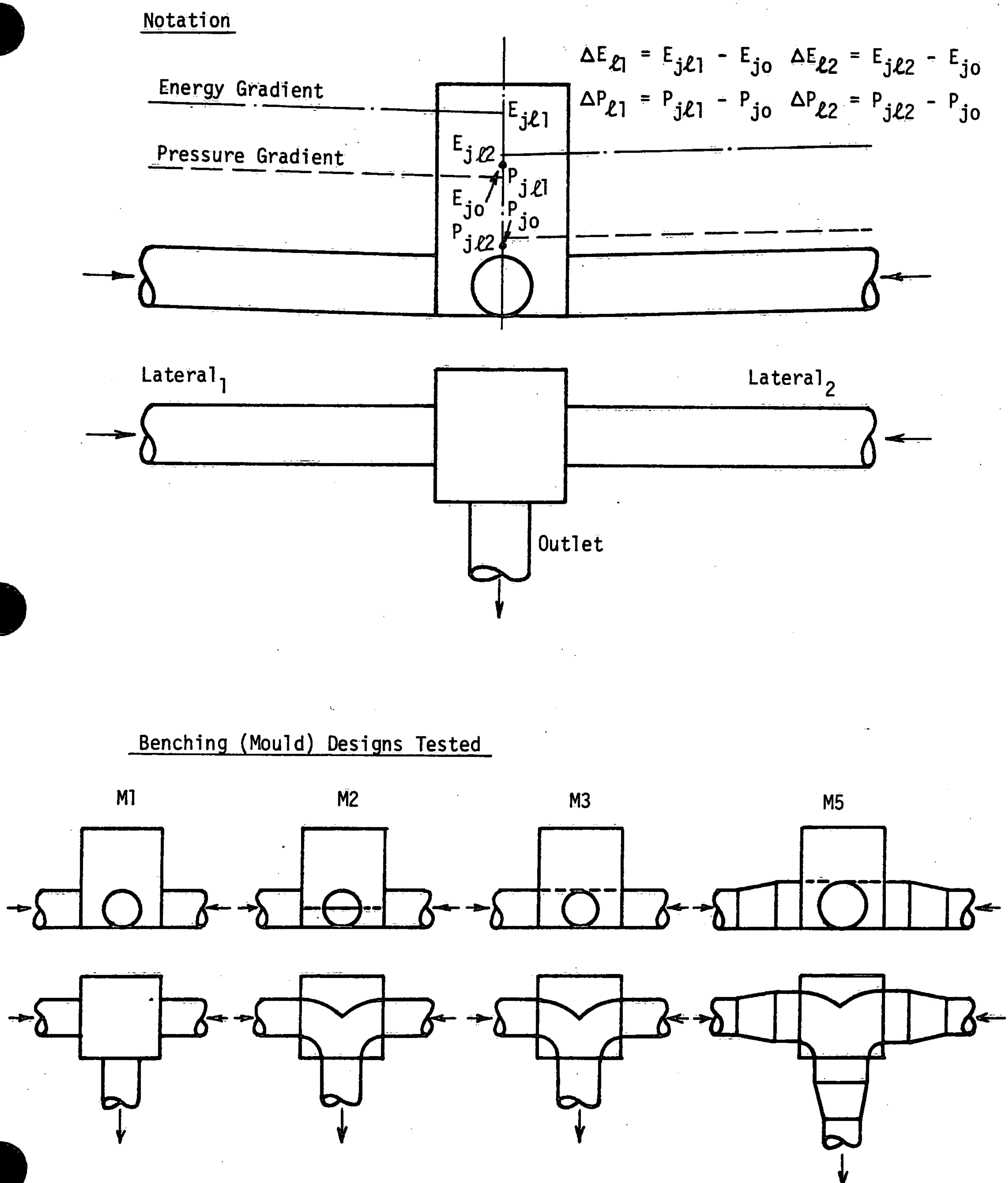


Fig.15. Junction of Two Opposed Laterals

Two Opposed Laterals). This type of benching should provide some guidance to the flows merging at the junction and maintain a good access to the manhole.

Mould M3 represents an improved variation of mould M2 which was obtained by extending the side walls to the pipe crown and placing the horizontal benches at that level. Such an arrangement should provide more flow guidance and, therefore, lower head losses.

Mould M5 was proposed to further lower head losses at the junction. It is, in principle, mould M3 with expanded channel dimensions at the junction. The alignment between the regular sewer pipes and the expanded junction channels is obtained by means of eccentric pipe expanders/reducers of standard design. By expanding the flow cross-section at the junction, the flow velocities and the corresponding head losses are reduced. This mould produced the lowest head losses in the earlier phases of this study.

Although the above junction moulds do not exhasust all possible geometries, they represent a wide range of conditions from the worst case (M1) to the best practical case (M5). Experimental results obtained for these moulds can then be used to make inferences for other designs.

Manhole Base Shape

The APWA survey indicated that although the round-base manholes are predominant in municipal practice, square-base (or rectangular) manholes are used by some Canadian municipalities, or in the case of large pipes. Consequently, both types of manholes were tested. The round-base manhole was obtained by placing an insert into the square-base manhole.

Details of experimental procedures were given earlier in Chapter 3. A sketch of the experimental apparatus is shown in Fig. 16 - Experimental Apparatus (Phase 3).

4.3.3 Pressurized Flow Results

The head losses in pressurized flow were investigated most thoroughly, because such conditions produce the highest losses and consequently reduce most the system capacity. In total, 14 runs dealt with pressurized flow. In all runs, head losses in both laterals were observed and the corresponding head loss coefficients ranged from 0.5 to 2.5. As expected, the lower values corresponded to the hydraulically effective moulds (M2, M3 and M5) and $Q_{\ell 1} = Q_{\ell 2}$.

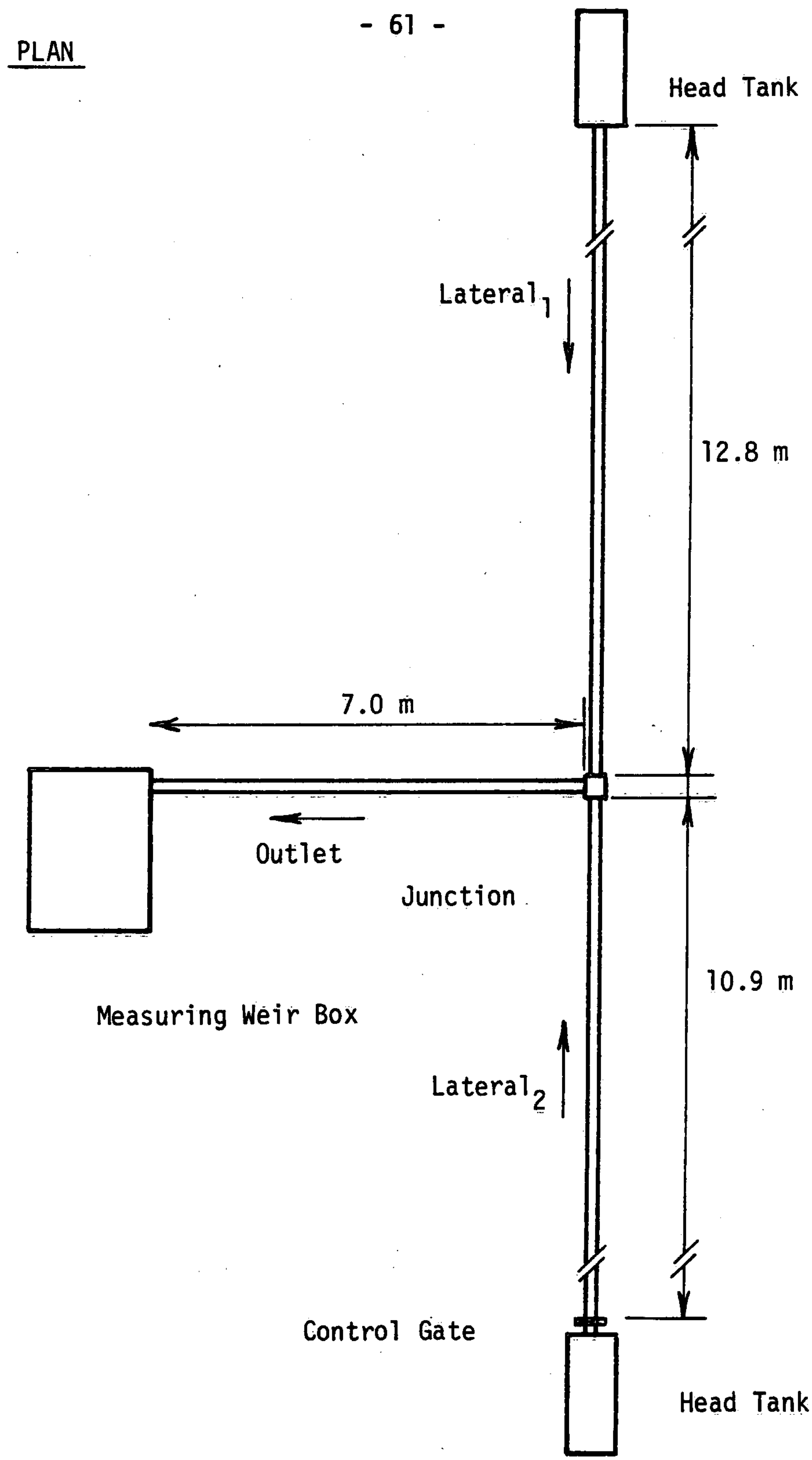


Fig.16. Experimental Apparatus(Phase 3)

Observations of flow conditions at the junction manhole indicated fairly quiescent conditions for hydraulically effective moulds (M2, M3 and M5) and comparable lateral flows. For mould M1 and very high or low $Q_{\ell 1}/Q_o$, large disturbances accompanied by large eddies and vortices developed at the junction and the losses increased correspondingly.

Following the procedures from the preceding chapter, the loss coefficients K and K_p were plotted in Figs. 17 - Energy Head Loss Coefficient vs. Q_ℓ/Q_o, and 18 - Pressure Head Loss Coefficient vs. Q_ℓ/Q_o versus the relative discharge. Such plots were then approximated by regression curves (quadratic polynomials) to smooth the data and to facilitate further processing. High values of the regression coefficient were found in all cases (r^2 = 0.9) except for mould M5.

For the overall evaluation of individual runs, five coefficients analogous to those used in the preceding section were used. Definitions of these coefficients follow; their numerical values are listed in Table 14 - Junctions of Two Opposed Laterals: Experimental Program and Mean Loss Coefficients.

The total power loss at the junction of two opposed laterals can be expressed as:

$$L_{pw} = \rho g \, (E_{\ell 1} \, Q_{\ell 1} + E_{\ell 2} \, Q_{\ell 2} - E_o Q_o) \tag{27}$$

where subscripts 1 and 2 refer to the left and right lateral, respectively (see Fig. 15 - Junction of Two Opposed Laterals), and $Q_{\ell 1}$ + $Q_{\ell 2}$ = Q_o. The power loss coefficient, C_p, is then expressed as the total power loss divided by the power of flow leaving the junction ($\rho g \, E_o \, Q_o$):

$$C_p = x \, K_{p\ell 1} + x^3 + K_{p\ell 2} \, (1 - x) + (1 - x)^3 - 1 \tag{28}$$

where $x = Q_{\ell 1}/Q_o$. The mean power loss coefficient is then defined as

$$\bar{C}_p = \int_0^1 C_\sigma dx \tag{29}$$

and, analogously, the mean head and pressure loss coefficients are defined as:

$$\bar{K}_\ell = \int_0^1 K_\ell dx \qquad \bar{K}_{p\ell} = \int_0^1 K_{p\ell} dx \tag{30}$$

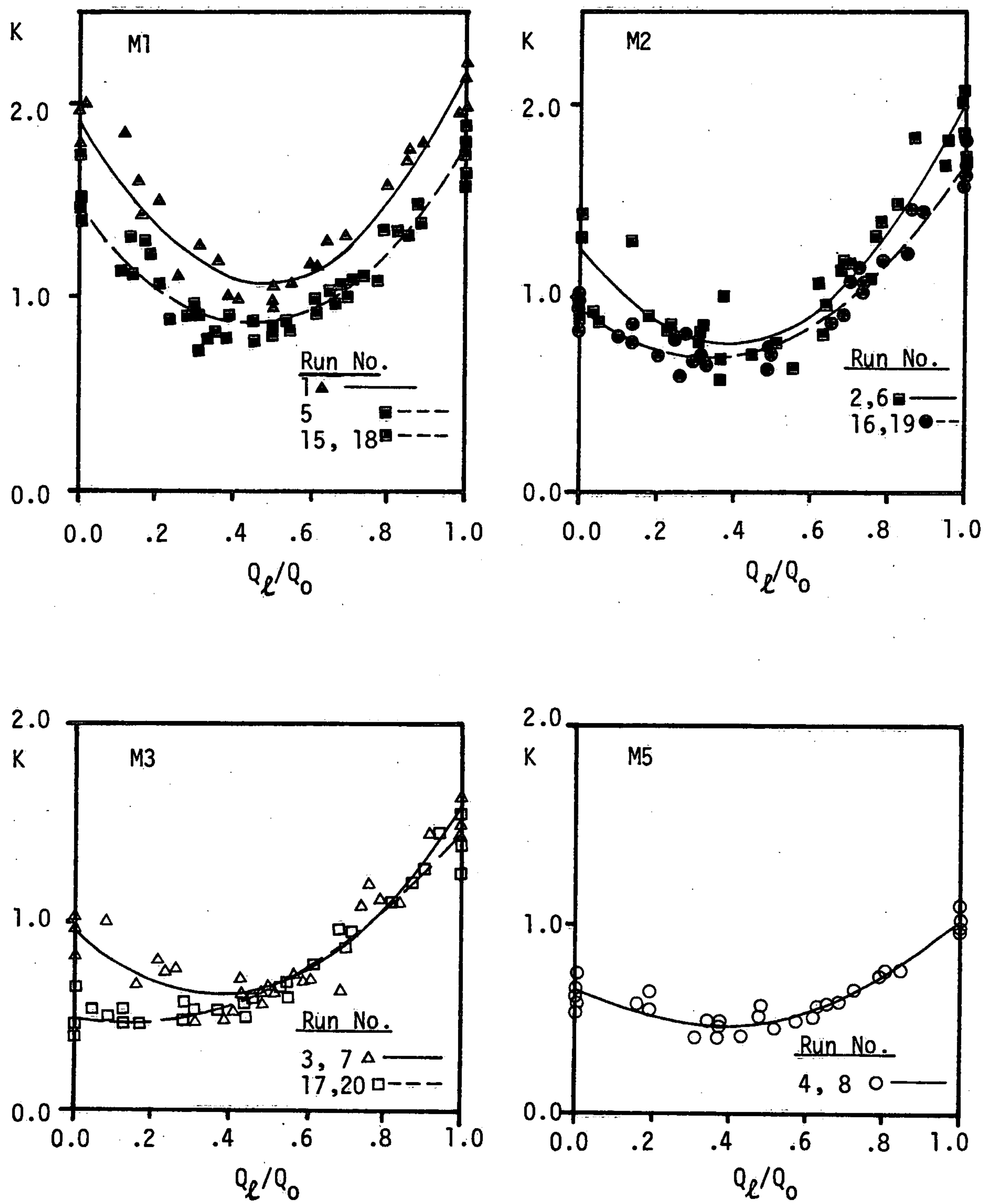


Fig.17. Energy Head Loss Coefficient vs. Q_ℓ/Q_o(Phase 3)

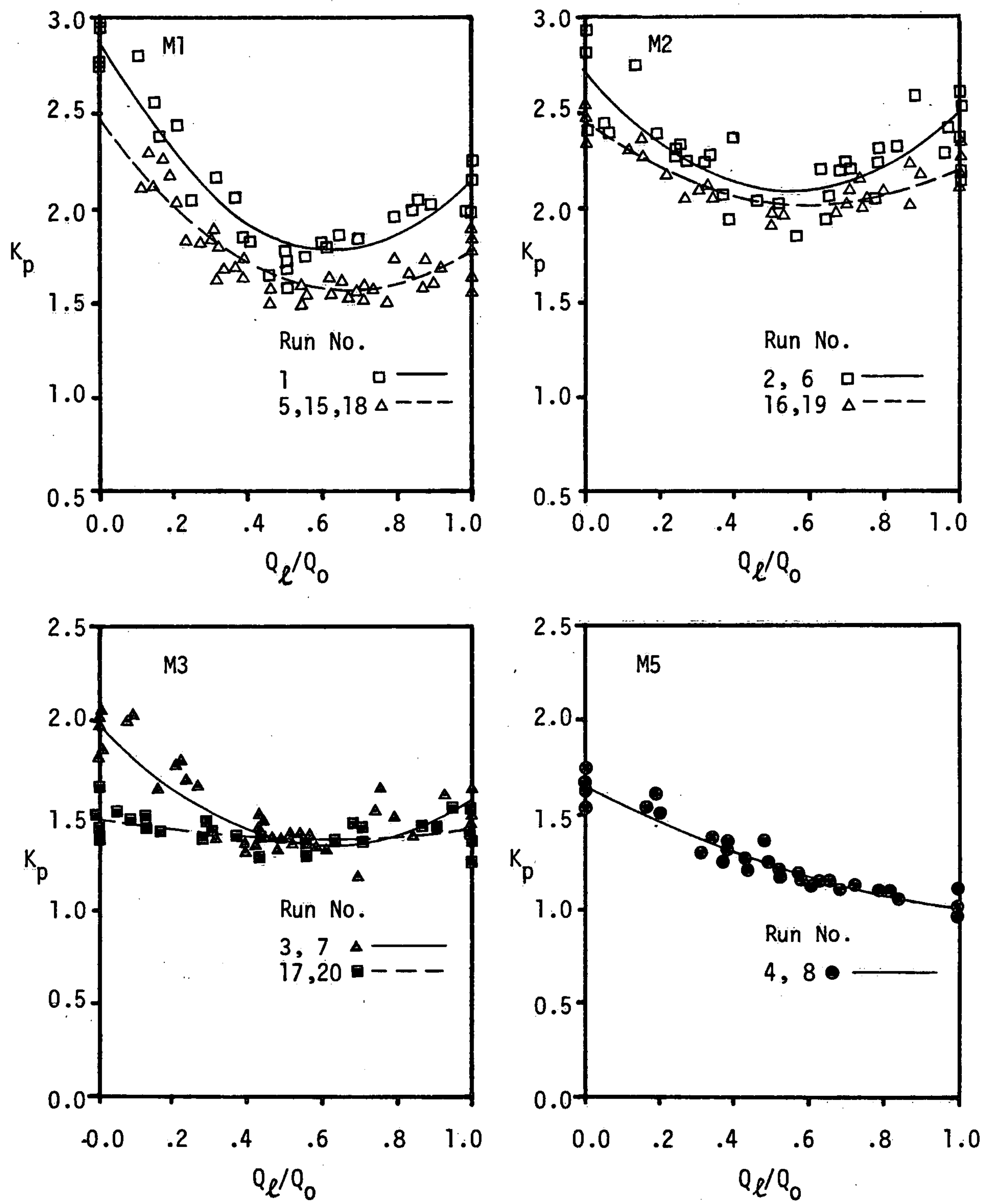


Fig.18. Pressure Head Loss Coefficient vs. Q_ℓ/Q_o (Phase 3)

Note that because of the symmetry of the junction, for mean values, indentical results are obtained for both laterals and, consequently, only one pair of coefficients designated simply K_ℓ and $K_{p\ell}$ is given. The mean values of coefficients K_ℓ and $K_{p\ell}$ are given in Table 14 - Junctions of Two Opposed Laterals: Experimental Program and Mean Loss Coefficients. Discussion of individual experimental factors is given below.

It should be also noted that the relationship between the head and pressure loss coefficients is given by the following relationships derived from basic definitions:

$$K_{p\ell 1} = K_{\ell 1} + 1 - x^2 \tag{31}$$

$$K_{p\ell 2} = K_{\ell 2} + 1 - (1 - x)^2 \tag{32}$$

where $x = Q_{\ell 1}/Q_o$ and $D_{\ell 1} = D_{\ell 2} = D_o$.

Relative Lateral Discharge

Loss coefficients need to be plotted only for one branch, because they are the same for both branches.

Observed head losses varied significantly with Q_ℓ/Q_o. Practically all graphs of K versus Q_ℓ/Q_o had a characteristic concave shape, with the minimum K occurring close to $Q_\ell/Q_o = 0.5$ when the forces of both incoming lateral flows were balanced. Conceivably, such a case of dynamic balance is rather unsteady and relatively large variations of K's were observed in this region.

In general, the values of K increased for both low and high Q_ℓ/Q_o's. With the possible exception of mould M1, the limiting cases of $Q_{\ell 1}/Q_o = 1$ ($Q_{\ell 2}/Q_o = 0$) do not correspond exactly to the similar manholes with 90° bends because of differences in the benching design (compare Fig. 6 - Manhole with a 90° Bend, and Fig. 15 - Junction of Two Opposed Laterals).

Relative Manhole Size

On average, the head losses for larger b/D_o, or D_{mh}/D_o, were about 10% greater than those for smaller manholes (smaller b/D_o, D_{mh}/D_o). In view of experimental uncertainties, such differences are not very significant.

Manhole Benching (Moulds)

The effect of benching on mean losses at the junction was again very pronounced. As in the earlier phases, the highest losses were found in the case without benching (mould M1). On the average (i.e., for $0 \leq x \leq 1$), such power losses were reduced by 8% for mould M2, 26% for mould M3, and 50% for mould M5. It was further noted that although M5 produced mean losses significantly lower than those produced by M3, most of this reduction took place for very low or very high Q_ℓ/Q_o's. In the region of comparable lateral inflows, say $Q_{\ell 1}/Q_o$ = 0.4 to 0.6, the differences in the performance of both moulds were rather small and the use of the more expensive design M5 would be hardly justified.

Base Shape

The base shape may influence junction losses by inducing formation of certain flow patterns inside the junction which may contribute to the overall loss. When comparing paired results for round- and square-base manholes, on the average, no significant differences between both sets of data were found. Thus in general, the effect of the base shape was not significant.

Junction Surcharge

In the first two phases of the study, the junction surcharge could be omitted as an independent variable on the basis of experimental data from various sources. To verify this procedure for junctions of two opposed laterals, for each Q_ℓ/Q_o, several surcharge heads were used. Although the corresponding head loss coefficients exhibited certain variations with the surcharge head, such variations were relatively small and random. Thus considering the experimental errors involved, no clear influence of the junction surcharge head was detected and all the observed data were used to fit a single curve depicting the variation of K with Q_ℓ/Q_o.

Lateral Pipe Size ($D_{\ell 1}/D_o$, $Q_{\ell 2}/Q_o$)

Although only the case with equal lateral pipe sizes ($D_{\ell 1} = D_{\ell 2} = D_o$) was studied, it should be recognized that higher losses would be found for unequal lateral sizes. This follows from the preceding phase of this study as well as from Sangster et al. data (15). The latter reference should be consulted for guidance in this respect. Losses at junctions of two opposed unequal laterals can be somewhat reduced by offsetting the laterals.

4.3.4 Open-Channel Flow Results

The scope of experiments for open-channel flow was rather limited - six runs altogether. All these runs were made for large pipes (6 in, 152 mm), both the square- and round-base manholes, and for several moulds. Note that in the case of the round-base manhole, moulds M3 and M5 yield identical geometries as the square-base manhole and, consequently, there was no need to repeat the testing of such installations.

The results for open-channel flow are shown in Fig. 19 - Head Loss Coefficient vs. Q_ℓ/Q_o - Open-Channel Flow. In comparison to the pressurized flow results, it is obvious that the losses in the open-channel flow are significantly smaller with all the mean K values falling in the range from 0.0 to 0.7. This follows from smaller changes in the channel geometry at the junction, particularly when benchings are used at the junction.

The head loss coefficient exhibited relatively small variations with Q_r. The highest mean loss coefficients were found for mould M1 - K = 0.48 and 0.41 for the square- and round-base manholes, respectively. These values were sharply reduced for mould M2 (about 0.12). Comparable values were found for M3 (0.12) and M5 (0.17). All these data were affected by increased experimental uncertainty which was typical for open-channel flow experiments.

4.3.5 Sulphide Gas Releases

As discussed earlier, sulphide gas releases at junctions in sanitary and combined sewers are enhanced by flow turbulence at junctions. Using the qualitative observations of turbulence at the junctions studied, the susceptibility of junctions to sulphide gas releases is evaluated in Table 15 - Evaluation of Junctions of Two Opposed Laterals for Sulphide Gas Releases.

TABLE 15. EVALUATION OF JUNCTIONS OF TWO OPPOSED LATERALS FOR SULPHIDE GAS RELEASES

Benching (Mould)	Turbulence Rating	Susceptibility to Sulphide Gas Releases
M1	2 (low flows) - 3 (high flows)	medium - high
M2	2	medium
M3	1	low
M5	1	low

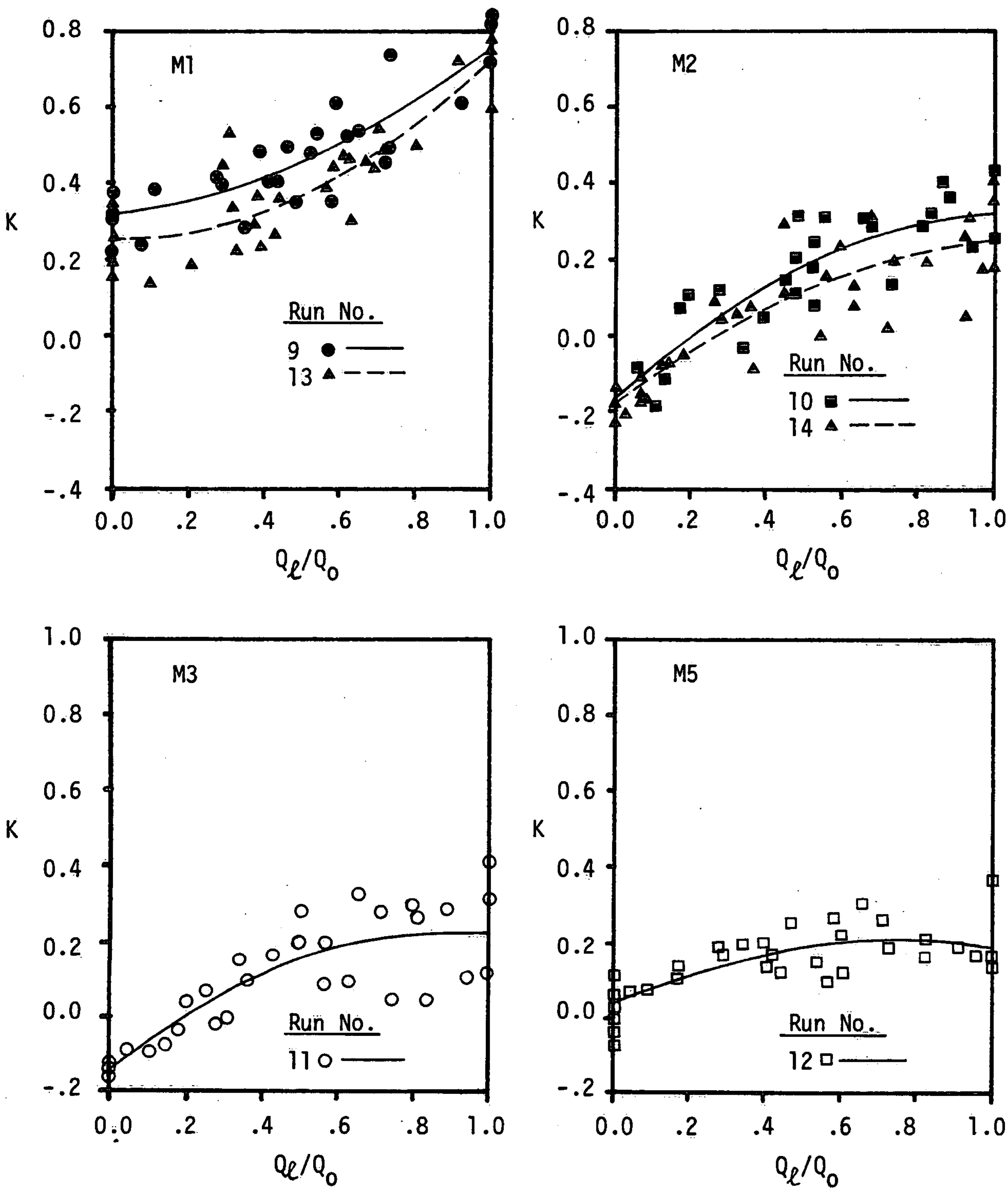


Fig.19. Head Loss Coefficient vs. Q_ℓ/Q_o - Open-Channel Flow(Phase 3)

Where sulphide gas releases are of concern, designs M3 or even M5 are recommended.

4.3.6 Design Data

The earlier described experimental head loss coefficients were approximated by regression equations which were then used to produce tables of head and pressure loss coefficients for various relative discharges and junctions geometries. Detailed tables of such coefficients are given in the Appendix. Only a summary table giving one set of data for each mould is given here as Table 16 - Pressure Change and Head Loss Coefficients for a Junction with Two Opposed Laterals. This summary combines four subsets for moulds M1 to M3 and two subsets for M5. The standard deviations of subset data about the mean given in the summary table varied from 0.01 to 0.28. In the practical range of relative lateral flows ($0.2 \leq Q_\ell/Q_0 \leq 0.8$), however, the above standard deviations varied from 0.01 to 0.15 and the coefficients from Table 16 - Pressure Change and Head Loss Coefficients for a Junction with Two Opposed Laterals, may be used confidently in design.

The energy head loss coefficient K varied from 0.5 to 1.9. The minimum value was found for M5 and a fairly wide range of relative lateral discharges ($0.2 \leq Q_\ell/Q_0 \leq 0.6$). The maxiumum values were found for $Q_\ell/Q_0 = 1$ and moulds M1 and M2. The pressure loss coefficient varied from 1.0 to 2.6. The highest values were found for the cases where the incoming flow was smaller than the opposing flow.

4.3.7 Design Examples

For illustration of the design data given in the preceding section, two simple examples are presented below.

Example No. 1

Establish pressure and head losses at a surcharged junction of two opposed laterals for the following conditions:

Sewer diameters - $D_{\ell 1} = D_{\ell 2} = D_0 = 0.61$ m (24 in)

Discharges - $Q_{\ell 1} = 0.175$ m^3/s (6.2 cfs),
$Q_{\ell 2} = 0.409$ m^3/s (14.4 cfs), and
$Q_0 = 0.584$ m^3/s (20.6 cfs)

Manhole - a round-base manhole, 1.22 m (4 ft) in diameter, mould M2.

TABLE 16. PRESSURE CHANGE AND HEAD LOSS COEFFICIENTS FOR A JUNCTION WITH TWO OPPOSED LATERALS ($D_{\ell 1} = D_{\ell 2} = D_o$)

	Pressure Change Coefficients							
	$K_{p\ell 1}$				$K_{p\ell 2}$			
$Q_{\ell 1}/Q_o$	M1	M2	M3	M4	M1	M2	M3	M4
0.0	2.6	2.1	1.7	1.7	1.9	1.9	1.5	1.0
0.1	2.3	1.9	1.6	1.6	1.8	1.8	1.4	1.1
0.2	2.1	1.8	1.5	1.5	1.7	1.6	1.4	1.1
0.3	1.9	1.7	1.5	1.4	1.6	1.6	1.4	1.1
0.4	1.8	1.6	1.4	1.3	1.6	1.5	1.4	1.2
0.5	1.7	1.5	1.4	1.2	1.7	1.5	1.4	1.2
0.6	1.6	1.5	1.4	1.2	1.8	1.6	1.4	1.3
0.7	1.6	1.6	1.4	1.1	1.9	1.7	1.5	1.4
0.8	1.7	1.6	1.4	1.1	2.1	1.8	1.5	1.5
0.9	1.8	1.8	1.4	1.1	2.3	1.9	1.6	1.6
1.0	1.9	1.9	1.5	1.0	2.6	2.1	1.7	1.7

	Energy Head Loss Coefficients							
	$K_{\ell 1}$				$K_{\ell 2}$			
$Q_{\ell 1}/Q_o$	M1	M2	M3	M4	M1	M2	M3	M4
0.0	1.6	1.1	0.7	0.7	1.9	1.9	1.5	1.0
0.1	1.3	0.9	0.6	0.6	1.6	1.6	1.3	0.9
0.2	1.1	0.8	0.6	0.5	1.3	1.3	1.0	0.7
0.3	1.0	0.8	0.6	0.5	1.1	1.1	0.9	0.6
0.4	0.9	0.7	0.6	0.5	1.0	0.9	0.7	0.5
0.5	0.9	0.8	0.6	0.5	0.9	0.8	0.6	0.5
0.6	1.0	0.9	0.7	0.5	0.9	0.7	0.6	0.5
0.7	1.1	1.1	0.9	0.6	1.0	0.8	0.6	0.5
0.8	1.3	1.3	1.0	0.7	1.1	0.8	0.6	0.5
0.9	1.6	1.6	1.3	0.9	1.3	0.9	0.6	0.6
1.0	1.9	1.9	1.5	1.0	1.6	1.1	0.7	0.7

Step 1 - Calculate the outlet velocity head

$$H_o = V^2/2\,g = \left(\frac{Q_o}{A_o}\right)^2/2\,g$$

$$= (0.584/0.292)^2/2 \times 9.81 = 0.204 \text{ m } (0.67 \text{ ft})$$

Step 2 - For $Q_r = Q_{\ell 1}/Q_o = 0.175/0.584 = 0.3$ and mould M2, read the loss coefficients from Table 16 as follows:

$K_{p\ell 1} = 1.7$ $\quad$ $K_{p\ell 2} = 1.6$

$K_{\ell 1} = 0.8$ $\quad$ $K_{\ell 2} = 1.1$

Step 3 - Calculate the losses for the above coefficients

$$\Delta P_{\ell 1} = K_{p\ell 1} H_o = 1.7 \times 0.204 = 0.347 \text{ m } (1.14 \text{ ft})$$

$$\Delta P_{\ell 2} = K_{p\ell 2} H_o = 1.6 \times 0.204 = 0.326 \text{ m } (1.07 \text{ ft})$$

$$\Delta E_{\ell 1} = K_{\ell 1} H_o = 0.8 \times 0.204 = 0.163 \text{ m } (0.53 \text{ ft})$$

$$\Delta E_{\ell 2} = K_{\ell 2} H_o = 1.1 \times 0.204 = 0.224 \text{ m } (0.73 \text{ ft})$$

The pressure changes in both laterals are comparable (0.347 m and 0.326 m, respectively). The lateral with the higher discharge experienced a higher head loss (0.224 m, or 0.73 ft) than the other one (0.163 m or 0.53 ft).

Example No. 2

Calculate head losses at the junction from Example No. 1 for a subcritical open-channel flow characterized by the following data:

Discharges - $Q_{\ell 1} = 0.160 \text{ m}^3/\text{s}$ (5.6 cfs),

$Q_{\ell 2} = 0.240 \text{ m}^3/\text{s}$ (8.5 cfs), and

$Q_o = 0.400 \text{ m}^3/\text{s}$ (14.1 cfs)

Depth of flow in the outlet - h = 0.55 m (1.8 ft).

Step 1 - Calculate the outlet velocity head as

$$H_o = (Q_o/A_o)^2/2\,g$$

$$= (0.4/0.2767)^2/2 \times 9.81 = 0.107 \text{ m}$$

Step 2 - Determine the head loss coefficients from Fig. 19 for mould M2 -

The relative discharge in the first lateral is $Q_r = Q_{\ell 1}/Q_o = 0.16/0.4 = 0.4$ and the corresponding head loss coefficient is $K_{\ell 1} = 0.11$.

In the second lateral, the relative discharge is $Q_r = 0.6$ and the corresponding coefficient $K_{\ell 2} = 0.19$.

Step 3 - Calculate the head losses

$$\Delta E\ell 1 = K\ell 1\ Ho = 0.11 \times 0.107 = 0.012 \text{ m } (0.04 \text{ ft})$$

$$\Delta E\ell 2 = K\ell 2\ Ho = 0.19 \times 0.107 = 0.020 \text{ m } (0.07 \text{ ft}).$$

The calculated head losses are fairly small and certainly much smaller than those calculated for pressurized flow.

4.3.8 Summary

The principal findings of the last study phase which dealt with junctions of two opposed laterals are summarized below.

(1) Head losses at junctions with two opposed laterals are affected by both the junction geometry and the relative discharge $Q_r = Q_\ell/Q_o$. Generally, the losses increased with an increasing deviation of Q_r from the value of 0.5.

(2) Among the geometrical parameters of junctions with identical lateral diameters operating under pressure, the benching (mould) had the most pronounced effect on the head loss, followed by the base shape and the relative manhole width. The lowest head loss coefficients were found for mould M5, followed by municipal designs described as moulds M3 and M2. The arrangement without any benching, mould M1, produced by far the highest losses. The loss coefficient for M5 amounted to only 41% of that for M1 and the coefficients for M2 and M3 fell between these two extremes. Although the square-base manhole produced slightly higher losses than the round-base manholes, such an increase (7%) was hardly significant in view of experimental uncertainties. The relatively wider manholes produced slightly

lower losses (by 6%), but this difference seems insignificant.

(3) Head losses for the open-channel flow conditions were much lower than those in the pressurized flow. In fact, the highest observed head loss coefficient was 0.48 for mould M1, as compared to the value of 3.0 corresponding to the pressurized flow. The coefficients for the remaining moulds varied from 0.10 to 0.16.

(4) To minimize the losses at junctions with two opposed laterals, such junctions should be designed with identical diameters of both laterals and hydraulically efficient benchings, such as moulds M5, M3 and M2.

5.0 SUMMARY AND CONCLUSIONS

Pressure and head losses at sewer pipe junctions are controlled by both flow characteristics and junction geometry. In pressurized flow, the most important flow variable was the relative lateral inflow (Q_ℓ/Q_0) for junctions with more than two pipes. Other variables could be either completely neglected (e.g., the Froude number), or neglected in regions where their value is above a certain threshold. In particular, the viscous forces effects were negligible for Re 10^4 and in some cases, no surcharge effects were noted for S/D_0 as low as 1.3.

Among the junction geometrical parameters, the important ones are the relative pipe sizes (D_m/D_0, D_ℓ/D_0), junction benching, and the pipe alignment. The remaining two parameters studied, the base shape and the relative manhole size (b/D_0 or D_{mh}/D_0) were much less influential within the range of conditions studied. Because identical branch pipe diameters were used in most runs, the benching was the most important factor in these experiments. Further recommendations for individual junction designs follow.

Manholes with a 90° bend - the head loss coefficients were affected only by the junction geometry. For the cases studied, with no change in pipe diameter at the junction, the benching was the most important factor. The highest head or pressure losses were found for junctions without benching (M1), and even the benching at half the pipe diameter (M2) was not effective in reducing losses. Substantial reductions in losses, by almost one half, were achieved by installing a full pipe depth benching (M3). A similar design with an expanded pipe diameter immediately upstream and downstream of the junction (M5) produced losses equal to about one third of those corresponding to the case without benching (M1).

Junctions of a main with a lateral - the main flow variable was the relative lateral discharge $Q_r = Q_\ell/Q_0$. Head losses increased with an increasing Q_r. Minor differences between loss coefficients for the main and the lateral were observed. Although both coefficients increased with Q_r, the lateral coefficient increased more. For very low Q_r, the flow from the lateral experienced a small energy gain. Among the geometrical parameters, the lateral pipe diameter and the benching were particularly important. The losses in the main pipe increased with a decreasing lateral diameter. Among various benching designs, moulds M1 (no benching) and M2 produced comparable losses. Significant loss reductions were found for mould M3 and even greater reductions were observed for mould M5.

Junctions with two opposed laterals - these junctions were studied only for identical lateral diameters. Head losses were again strongly affected by the relative lateral flow $Q_r = Q_{\ell 1}/Q_o$. The lowest losses were observed in cases where both lateral flows were comparable ($Q_{\ell 1} \sim Q_{\ell 2}$). The highest losses resulted from unevenly distributed lateral inflows. Among the geometrical parameters, the benching was very important. Moulds M1 (no benching) and M2 produced similar losses, which were significantly reduced in the case of mould M3 and further reduced by mould M5. In the region of Q_r from 0.3 to 0.7, however, there was little difference in performance between M3 and M5 and the added expense connected with installing mould M5 would be hardly justified.

The experiments with sewer junctions operating under open-channel flow conditions were rather limited. The main objective of these experiments was to establish the magnitude of such losses in comparison to those for pressurized flow conditions. In all cases, the head loss coefficients for open-channel flow were substantially smaller than those for pressurized flow. Head losses were exceptionally small because of smaller loss coefficients and lower velocities in open-channel flow. The accurate measurement of such small losses was rather difficult and increased experimental uncertainties were noticed in open-channel flow runs. Hydraulically efficient benchings (particularly M3 and M5) reduced junction head losses.

A qualitative evaluation of sulphide gas releases at junctions has been made on the basis of qualitative observations of turbulence at junctions assuming that flow turbulence is the main reason for such releases. Generally, the susceptibility of junctions to sulphide gas releases was low for junctions with effective benching (moulds M3 and M5), equal pipe diameters, higher depths of surcharge, and intermediate lateral inflows (Q_r = 0.3 to 0.7).

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APPENDIX TABLES

TABLE A.1. JUNCTIONS OF A MAIN WITH A LATERAL - EXPERIMENTAL DATA FOR M1 ($D_\ell = D_m = D_o$)

Mould No.	D_{mh}/D_o* or b/D_o*	Q_ℓ/Q_o	K_m	K_ℓ	K_{pm}	$K_{p\ell}$
1	2.3	0.0	0.3	-0.7	0.3	0.3
1	2.3	0.1	0.4	-0.4	0.6	0.6
1	2.3	0.2	0.5	-0.1	0.9	0.8
1	2.3	0.3	0.6	0.1	1.1	1.1
1	2.3	0.4	0.7	0.4	1.3	1.3
1	2.3	0.5	0.8	0.7	1.5	1.4
1	2.3	0.6	0.8	1.0	1.7	1.6
1	2.3	0.7	0.9	1.2	1.8	1.7
1	2.3	0.8	1.0	1.5	2.0	1.9
1	2.3	0.9	1.1	1.8	2.1	2.0
1	2.3	1.0	1.2	2.1	2.2	2.1
1	4.6	0.0	0.4	-0.6	0.4	0.4
1	4.6	0.1	0.6	-0.2	0.8	0.8
1	4.6	0.2	0.7	0.1	1.0	1.0
1	4.6	0.3	0.8	0.4	1.3	1.3
1	4.6	0.4	0.9	0.6	1.5	1.5
1	4.6	0.5	0.9	0.9	1.7	1.6
1	4.6	0.6	1.0	1.1	1.8	1.7
1	4.6	0.7	1.0	1.3	1.9	1.8
1	4.6	0.8	1.0	1.5	2.0	1.8
1	4.6	0.9	1.0	1.6	2.0	1.8
1	4.6	1.0	1.0	1.8	2.0	1.8

* Data for square and round manholes grouped together.

TABLE A.2. JUNCTIONS OF A MAIN WITH A LATERAL - EXPERIMENTAL DATA FOR M2 ($D_\ell = D_m = D_o$)

Mould No.	$\frac{D_{mh}}{D_o}$* or $\frac{b}{D_o}$*	$\frac{Q_\ell}{Q_o}$	K_m	K_ℓ	K_{pm}	$K_{p\ell}$
2	2.3	0.0	0.2	-0.8	0.2	0.2
2	2.3	0.1	0.3	-0.5	0.5	0.5
2	2.3	0.2	0.4	-0.2	0.8	0.8
2	2.3	0.3	0.5	0.1	1.1	1.0
2	2.3	0.4	0.6	0.4	1.3	1.2
2	2.3	0.5	0.7	0.6	1.5	1.4
2	2.3	0.6	0.8	0.9	1.6	1.5
2	2.3	0.7	0.8	1.1	1.7	1.6
2	2.3	0.8	0.9	1.4	1.8	1.7
2	2.3	0.9	0.9	1.6	1.9	1.8
2	2.3	1.0	0.9	1.8	1.9	1.9
2	4.6	0.0	0.4	-0.6	0.4	0.4
2	4.6	0.1	0.5	-0.3	0.7	0.7
2	4.6	0.2	0.6	0.0	1.0	1.0
2	4.6	0.3	0.7	0.3	1.2	1.2
2	4.6	0.4	0.8	0.5	1.4	1.4
2	4.6	0.5	0.8	0.7	1.6	1.5
2	4.6	0.6	0.8	0.9	1.7	1.6
2	4.6	0.7	0.8	1.1	1.8	1.6
2	4.6	0.8	0.8	1.3	1.8	1.7
2	4.6	0.9	0.8	1.4	1.8	1.6
2	4.6	1.0	0.8	1.6	1.8	1.6

* Data for square and round manholes grouped together.

TABLE A.3. JUNCTIONS OF A MAIN WITH A LATERAL - EXPERIMENTAL DATA FOR M3 ($D_\ell = D_m = D_o$)

Mould No.	$\frac{D_{mh}}{D_o}$* or $\frac{b}{D_o}$*	$\frac{Q_\ell}{Q_o}$	K_m	K_ℓ	K_{pm}	$K_{p\ell}$
3	2.3	0.0	0.2	-0.8	0.2	0.2
3	2.3	0.1	0.3	-0.5	0.5	0.5
3	2.3	0.2	0.4	-0.2	0.7	0.8
3	2.3	0.3	0.5	0.1	1.0	1.0
3	2.3	0.4	0.5	0.3	1.1	1.1
3	2.3	0.5	0.6	0.5	1.3	1.2
3	2.3	0.6	0.6	0.7	1.4	1.3
3	2.3	0.7	0.6	0.9	1.5	1.4
3	2.3	0.8	0.6	1.0	1.6	1.4
3	2.3	0.9	0.6	1.1	1.6	1.3
3	2.3	1.0	0.5	1.2	1.5	1.2
3	4.6	0.0	0.4	-0.6	0.4	0.4
3	4.6	0.1	0.5	-0.3	0.7	0.7
3	4.6	0.2	0.5	-0.1	0.9	0.9
3	4.6	0.3	0.6	0.2	1.1	1.1
3	4.6	0.4	0.6	0.4	1.3	1.2
3	4.6	0.5	0.7	0.6	1.4	1.4
3	4.6	0.6	0.7	0.8	1.5	1.5
3	4.6	0.7	0.7	1.0	1.6	1.5
3	4.6	0.8	0.7	1.2	1.6	1.5
3	4.6	0.9	0.7	1.3	1.6	1.5
3	4.6	1.0	0.6	1.4	1.6	1.4

* Data for square and round manholes grouped together.

TABLE A.4. JUNCTIONS OF A MAIN WITH A LATERAL - EXPERIMENTAL DATA FOR M5 ($D_\ell = D_m = D_o$)

Mould No.	$\frac{D_{mh}}{D_o}$* or $\frac{b}{D_o}$*	$\frac{Q_\ell}{Q_o}$	K_m	K_ℓ	K_{pm}	$K_{p\ell}$
5	2.3	0.0	0.3	-0.3	0.3	0.7
5	2.3	0.1	0.3	-0.2	0.5	0.8
5	2.3	0.2	0.3	-0.1	0.7	0.9
5	2.3	0.3	0.3	0.0	0.8	0.9
5	2.3	0.4	0.3	0.2	1.0	1.0
5	2.3	0.5	0.3	0.3	1.1	1.0
5	2.3	0.6	0.4	0.4	1.2	1.0
5	2.3	0.7	0.4	0.5	1.3	1.0
5	2.3	0.8	0.4	0.6	1.4	1.0
5	2.3	0.9	0.4	0.7	1.4	0.9
5	2.3	1.0	0.4	0.8	1.4	0.8

* Data for square and round manholes grouped together.

TABLE A.5. JUNCTIONS OF A MAIN WITH A LATERAL - EXPERIMENTAL DATA FOR M1 and M2 (D_ℓ = 0.5 D_o = 0.5 D_m)

Mould No.	$\frac{b}{D_o}$ *	$\frac{Q_\ell}{Q_o}$	K_m	K_ℓ	K_{pm}	$K_{p\ell}$
1	2.3	0.0	0.7	-0.8	0.7	0.2
1	2.3	0.1	0.9	-0.6	1.1	0.4
1	2.3	0.2	1.1	-0.3	1.4	0.6
1	2.3	0.3	1.2	-0.1	1.7	0.8
1	2.3	0.4	1.4	0.1	2.0	1.0
1	2.3	0.5	1.5	0.4	2.2	1.1
1	2.3	0.6	1.6	0.6	2.4	1.3
1	2.3	0.7	1.6	0.8	2.5	1.4
1	2.3	0.8	1.7	1.1	2.6	1.4
1	2.3	0.9	1.7	1.3	2.7	1.5
1	2.3	1.0	1.7	1.5	2.7	1.5
2	2.3	0.0	0.2	-0.9	0.2	0.1
2	2.3	0.1	0.5	-0.4	0.7	0.6
2	2.3	0.2	0.8	0.0	1.2	1.0
2	2.3	0.3	1.0	0.4	1.5	1.3
2	2.3	0.4	1.2	0.7	1.9	1.5
2	2.3	0.5	1.4	1.0	2.1	1.7
2	2.3	0.6	1.5	1.2	2.3	1.8
2	2.3	0.7	1.6	1.3	2.5	1.8
2	2.3	0.8	1.6	1.4	2.5	1.8
2	2.3	0.9	1.5	1.4	2.5	1.6
2	2.3	1.0	1.5	1.4	2.5	1.4

* Square base manholes.

TABLE A.6. JUNCTIONS OF A MAIN WITH A LATERAL - EXPERIMENTAL DATA FOR M3 and M5 (D_ℓ = 0.5 D_o = 0.5 D_m)

Mould No.	$\frac{b}{D_o}$ *	$\frac{Q_\ell}{Q_o}$	K_m	K_ℓ	K_{pm}	$K_{p\ell}$
3	2.3	0.0	0.4	-0.6	0.4	0.4
3	2.3	0.1	0.5	-0.4	0.7	0.6
3	2.3	0.2	0.7	-0.3	1.1	0.7
3	2.3	0.3	0.8	-0.3	1.3	0.6
3	2.3	0.4	0.9	-0.3	1.6	0.5
3	2.3	0.5	1.0	-0.5	1.8	0.3
3	2.3	0.6	1.1	-0.7	1.9	0.0
3	2.3	0.7	1.1	-1.0	2.0	-0.5
3	2.3	0.8	1.2	-1.4	2.1	-1.0
3	2.3	0.9	1.2	-1.8	2.2	-1.6
3	2.3	1.0	1.2	-2.4	2.2	-2.4
5	2.3	0.0	0.1	-0.1	0.1	0.8
5	2.3	0.1	0.2	-0.2	0.4	0.8
5	2.3	0.2	0.3	-0.4	0.7	0.6
5	2.3	0.3	0.4	-0.7	0.9	0.3
5	2.3	0.4	0.4	-1.0	1.1	-0.1
5	2.3	0.5	0.5	-1.4	1.2	-0.7
5	2.3	0.6	0.5	-2.0	1.4	-1.3
5	2.3	0.7	0.5	-2.6	1.4	-2.1
5	2.3	0.8	0.5	-3.3	1.5	-2.9
5	2.3	0.9	0.5	-4.1	1.5	-3.9
5	2.3	1.0	0.4	-5.0	1.4	-5.0

* Square base manholes.

TABLE A.7. JUNCTIONS OF TWO OPPOSED LATERALS - EXPERIMENTAL DATA FOR M1 ($D_{\ell 1} = D_{\ell 2} = D_o$)

Mould No.	$\frac{D_{mh}}{D_o}$* or $\frac{b}{D_o}$*	$\frac{Q_{\ell 1}}{Q_o}$	$K_{\ell 1}$	$K_{\ell 2}$	$K_{p\ell 1}$	$K_{p\ell 2}$
1	2.3	0.0	1.7	2.0	2.7	2.0
1	2.3	0.1	1.4	1.6	2.4	1.8
1	2.3	0.2	1.2	1.4	2.2	1.7
1	2.3	0.3	1.1	1.2	2.0	1.7
1	2.3	0.4	1.0	1.1	1.8	1.7
1	2.3	0.5	1.0	1.0	1.7	1.7
1	2.3	0.6	1.1	1.0	1.7	1.8
1	2.3	0.7	1.2	1.1	1.7	2.0
1	2.3	0.8	1.4	1.2	1.7	2.2
1	2.3	0.9	1.6	1.4	1.8	2.4
1	2.3	1.0	2.0	1.7	2.0	2.7
1	4.6	0.0	1.5	1.8	2.4	1.8
1	4.6	0.1	1.2	1.5	2.2	1.7
1	4.6	0.2	1.0	1.2	2.0	1.6
1	4.6	0.3	0.9	1.1	1.8	1.6
1	4.6	0.4	0.9	0.9	1.7	1.6
1	4.6	0.5	0.9	0.9	1.6	1.6
1	4.6	0.6	0.9	0.9	1.6	1.7
1	4.6	0.7	1.1	0.9	1.6	1.8
1	4.6	0.8	1.2	1.0	1.6	2.0
1	4.6	0.9	1.5	1.2	1.7	2.2
1	4.6	1.0	1.8	1.5	1.8	2.4

* Data for square and round manholes grouped together.

TABLE A.8. JUNCTIONS OF TWO OPPOSED LATERALS - EXPERIMENTAL DATA FOR M2 ($D_{\ell 1} = D_{\ell 2} = D_o$)

Mould No.	$\frac{D_{mh}}{D_o}$* or $\frac{b}{D_o}$*	$\frac{Q_{\ell 1}}{Q_o}$	$K_{\ell 1}$	$K_{\ell 2}$	$K_{p\ell 1}$	$K_{p\ell 2}$
2	2.3	0.0	1.3	2.1	2.3	2.1
2	2.3	0.1	1.1	1.7	2.1	1.9
2	2.3	0.2	0.9	1.4	1.9	1.7
2	2.3	0.3	0.8	1.1	1.7	1.6
2	2.3	0.4	0.8	0.9	1.6	1.6
2	2.3	0.5	0.8	0.8	1.6	1.6
2	2.3	0.6	0.9	0.8	1.6	1.6
2	2.3	0.7	1.1	0.8	1.6	1.7
2	2.3	0.8	1.4	0.9	1.7	1.9
2	2.3	0.9	1.7	1.1	1.9	2.1
2	2.3	1.0	2.1	1.3	2.1	2.3
2	4.6	0.0	0.9	1.7	1.9	1.7
2	4.6	0.1	0.8	1.4	1.8	1.6
2	4.6	0.2	0.7	1.2	1.7	1.6
2	4.6	0.3	0.7	1.0	1.6	1.5
2	4.6	0.4	0.7	0.9	1.5	1.5
2	4.6	0.5	0.8	0.8	1.5	1.5
2	4.6	0.6	0.9	0.7	1.5	1.5
2	4.6	0.7	1.0	0.7	1.5	1.6
2	4.6	0.8	1.2	0.7	1.6	1.7
2	4.6	0.9	1.4	0.8	1.6	1.8
2	4.6	1.0	1.7	0.9	1.7	1.9

* Data for square and round manholes grouped together.

TABLE A.9. JUNCTIONS OF TWO OPPOSED LATERALS - EXPERIMENTAL DATA FOR M3 ($D_{\ell 1} = D_{\ell 2} = D_o$)

Mould No.	$\frac{D_{mh}}{D_o}$* or $\frac{b}{D_o}$*	$\frac{Q_{\ell 1}}{Q_o}$	$K_{\ell 1}$	$K_{\ell 2}$	$K_{p\ell 1}$	$K_{p\ell 2}$
3	2.3	0.0	1.0	1.6	2.0	1.6
3	2.3	0.1	0.8	1.3	1.8	1.5
3	2.3	0.2	0.7	1.1	1.6	1.4
3	2.3	0.3	0.6	0.9	1.5	1.4
3	2.3	0.4	0.6	0.7	1.5	1.4
3	2.3	0.5	0.6	0.6	1.4	1.4
3	2.3	0.6	0.7	0.6	1.4	1.5
3	2.3	0.7	0.9	0.6	1.4	1.5
3	2.3	0.8	1.1	0.7	1.4	1.6
3	2.3	0.9	1.3	0.8	1.5	1.8
3	2.3	1.0	1.6	1.0	1.6	2.0
3	4.6	0.0	0.5	1.4	1.5	1.4
3	4.6	0.1	0.5	1.2	1.5	1.4
3	4.6	0.2	0.5	1.0	1.4	1.4
3	4.6	0.3	0.5	0.9	1.4	1.4
3	4.6	0.4	0.6	0.7	1.4	1.4
3	4.6	0.5	0.6	0.6	1.4	1.4
3	4.6	0.6	0.7	0.6	1.4	1.4
3	4.6	0.7	0.9	0.5	1.4	1.4
3	4.6	0.8	1.0	0.5	1.4	1.4
3	4.6	0.9	1.2	0.5	1.4	1.5
3	4.6	1.0	1.4	0.5	1.4	1.5

* Data for square and round manholes grouped together.

TABLE A.10. JUNCTIONS OF TWO OPPOSED LATERALS - EXPERIMENTAL DATA FOR M5 ($D_{\ell 1} = D_{\ell 2} = D_o$)

Mould No.	$\frac{D_{mh}}{D_o}$* or $\frac{b}{D_o}$*	$\frac{Q_{\ell 1}}{Q_o}$	$K_{\ell 1}$	$K_{\ell 2}$	$K_{p\ell 1}$	$K_{p\ell 2}$
5	2.3	0.0	0.7	1.0	1.7	1.0
5	2.3	0.1	0.6	0.9	1.6	1.1
5	2.3	0.2	0.5	0.7	1.5	1.1
5	2.3	0.3	0.5	0.6	1.4	1.1
5	2.3	0.4	0.5	0.5	1.3	1.2
5	2.3	0.5	0.5	0.5	1.2	1.2
5	2.3	0.6	0.5	0.5	1.2	1.3
5	2.3	0.7	0.6	0.5	1.1	1.4
5	2.3	0.8	0.7	0.5	1.1	1.5
5	2.3	0.9	0.9	0.6	1.1	1.6
5	2.3	1.0	1.0	0.7	1.0	1.7

* Data for square and round manholes grouped together.