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HIGH VELOCITIES IN SEWERS

A preliminary appraisal of factors influencing design

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FOREWORD

From the Chairman of the National Water Council Standing Committee on Sewers and Water Mains

I am very pleased to commend this report to all those concerned with the design of sewers with high velocities. Although the report is not a design guide, it nevertheless draws attention to the main factors that must be considered. I hope that the recommendations for further research will be implemented as soon as possible.

E C REED
Chairman

PREFACE

This report has been prepared at the request of the National Water Council Standing Committee on Sewers and Water Mains (Sub-Committee No 1; Hydraulic Design and Planning). When the water industry was reorganised in 1975, the NWC Standing Committee took over the function previously exercised by the Department of the Environment Working Party on Sewers and Water Mains, viz *'to advise on the design, construction, operation and maintenance of sewers, water mains and ancillary works'*.

One of the topics discussed in the first report of the DoE Working Party was the economic benefit that could be gained if no limit were set on the maximum velocity allowed in a sewer; this would permit sewers to be laid at gradients to suit the prevailing ground slope. The report went on to point out, however, that there were other factors to be taken into account and that care in the design was necessary.

As one of their first tasks, Sub-Committee No 1 of the NWC Standing Committee decided to look further at the economic benefits of relaxing the limitation on maximum velocity and to examine the hydraulic factors that influence design. While an economic study was being made, a questionnaire was sent to a number of water authorities in order to determine their policy on high velocity and their experience with sewers carrying high velocity flow. The replies to the questionnaire indicated that the general practice was not to restrict the maximum velocity and that no particular problems were yet evident. The Sub-Committee decided that the most appropriate next step would be to circulate a general statement on this topic, and therefore asked the Hydraulics Research Station to prepare a report.

This report is the result of that request. Its primary purpose is to set out the advantages to be gained from allowing high velocities, and to point out the principal factors to be considered by the designer, who may not always appreciate the more complex nature of high velocity flow. It must be emphasised, however, that this report is not a design manual or guide; it provides some references – although not an extensive bibliography – from which explicit design data can be obtained. Before any recommendations for design or for further research are made, a full literature survey needs to be carried out.

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1 INTRODUCTION

1.1 Traditionally, sewerage schemes were designed with a set limit for the maximum velocity (1), because it was believed that velocities higher than the limit would give rise to severe abrasion of the sewers. Although high velocities had to be avoided in the early brick sewers in order to prevent erosion of lime-mortar joints, research has shown that abrasion would not be a problem in modern sewers. Accordingly in 1968 the design recommendations in the Code of Practice on Sewerage (2) were changed and no limit was set for the maximum velocity (3).

1.2 Although removing the limit on maximum velocity enables more economical schemes to be built, factors are introduced into the design that, previously, it was not necessary to consider. This report summarises the research that led to the changes in the design recommendations for maximum velocities, discusses the savings in cost that result, lists other problems that will arise from the use of high velocities, and makes recommendations for further action.

2 EROSION OF SEWERS

2.1 In 1968, Vickers, Francis and Grant published the results of research on the erosion of sewers (4) that they had been carrying out under the sponsorship of CERA (now the Construction Industry Research and Information Association, CIRIA). This showed that the total amount of erosion in a sewer by grit-water mixtures was independent of the velocity of flow, although the distribution of the erosion around the periphery of the pipe was dependent on velocity. The experiments were carried out on specially prepared sand-cement specimens of low compressive strength using a number of different gradings of sediment and at water velocities of up to 7.6 m/s (25 ft/s). The tests were carried out on 1 m lengths of channel of semi-circular section; the radii were 100, 150 and 200 mm and the channels were running at depths of flow from 25 to 95 mm; the amount of erosion was determined by weighing and by measuring the changes in the cross-sectional geometry.

2.2 The tests did not show any correlation between the rate of erosion and velocity; however there was a correlation between the rate of erosion (measured in weight loss/second) and the product of the rate of grit discharge (for a given specific gravity of sediment) and the slope of the channel. It was found that as the velocity was increased, the erosion of the invert reduced, although it still remained the point of greatest wear.

2.3 No tests were carried out on the effects of discontinuities in the boundary geometry (such as the steps that can occur at the joints), but it was observed that such features produced localised areas of scour that were much more severe than the general scour in the remainder of the pipe.

2.4 Some tests were carried out on the erosion at bends, using a 100 mm diameter, pitch-fibre pipe, flowing full. In this case, the amount of erosion was found to be a function of the square of the velocity. Tests were carried out on bends of internal radii 38, 100 and 400 mm, but no quantitative data are given on the relation between the erosion and the bend radius.

2.5 Some substantiation for the experiments by Vickers, et al has been provided by Lysne, Tekle and Schei (5). Their experiments were carried out in Norway on three test lengths of pipe in series, each test length being laid at a different slope and consisting of a run of concrete and of PVC pipe, 100 mm diameter. Experiments were carried out with velocities of 2.5, 4.0 and 5.5 m/s with sand of mean diameter 1.1 mm and at concentrations of 0.8 and 1.6 per cent (whether by weight or volume is not stated). The results showed that *'the average erosion*

along the invert' (sic) was greatest for the velocity of 2.5 m/s, least for 4.0 m/s, and intermediate for 5.5 m/s. They also found that the erosion at joints was more severe than the average erosion along the pipe. The final results from the experimental work have not yet been published.

2.6 Although the Norwegian work supports to some extent the conclusions of Vickers et al as far as the relationship between velocity and erosion of the invert is concerned, in the discussion following their paper, Lysne did point out that although the maximum depth of erosion decreased with increasing velocity, the total amount of erosion around the pipe boundary increased with velocity. No experimental data have yet been published, so that it is not possible to quantify the increase in total erosion.

2.7 One of the main conclusions from the experiments of Vickers and Lysne is that discontinuities and bends are the main source of excessive wear at high velocities. In order to avoid problems at discontinuities it is necessary that a high standard of construction is obtained, with particular attention being paid to the joints to ensure that any boundary misalignment is kept to the minimum. Where bends do occur, as large a radius as possible should be used: this means that pipe costs will increase, as can be seen from the following table, which shows the effect on pipe costs of making a 90° change of direction by means of bends of different radii (assuming that there is no manhole at the bend).

Pipe diameter (mm)	Bends used for 90° change of direction	Radius of bend (mm)	Increase in pipe costs
150	$1 - 90^{\circ}$	230	–
	$2 - 45^{\circ}$	455	17 per cent of cost of 90° bend
	$4 - 22½^{\circ}$	915	51 per cent of cost of 90° bend
300	$2 - 45^{\circ}$	760	–
	$8 - 11¼^{\circ}$	1830	24 per cent of cost of $2–45^{\circ}$ bends (these are the two most commonly available bends at this diameter)

3 BENEFITS FROM REMOVING VELOCITY LIMITATION

3.1 The advantage of not having any limit on the maximum velocity is that the sewer can then be laid at a gradient that is similar to the general ground slope. Former practice, in steep country, would have been to lay the sewer at a gradient that was much flatter than the ground slope, in order to prevent the velocity from exceeding the allowable limit. This, in turn, would have required the provision of drop manholes (which are expensive) in order to minimise the volume of excavation, but even so, the sewer would still have been laid at a greater average depth than was essential from the point of view of maintaining the minimum cover to the pipes.

3.2 By eliminating the restriction on maximum velocity, reductions in the cost of sewerage schemes are thus possible. This is borne out by a

design exercise carried out by the Ipswich County Borough Council in 1973 (7), in which two alternative designs for the sewerage scheme in a new area of development were costed. The scheme chosen for the study was an area of 45 ha, mainly industrial, for which the sewerage system had been designed to cope with a 3 year storm without any restriction being placed on the maximum velocity. The overall ground slope was 0.03 (1/33) and the total length of sewer was 2527 m.

3.3 In the original design the diameters of the sewers ranged from 225 to 1425 mm; the maximum full-bore velocity was 5.1 m/s (16.7 ft/s) and the maximum part-full velocity was 5.8 m/s (19 ft/s). In the redesigned scheme the original plan alignment of the sewers was maintained but the maximum velocity was limited to 3.66 m/s; the range of sewer diameter was still from 225 to 1425 mm. The cost of the scheme without any velocity limitation was approximately 7.5 per cent cheaper than the scheme with an upper velocity limit of 3.66 m/s, the greatest part of the saving (5 per cent) arising from the elimination of backdrop manholes. The remaining saving of 2.5 per cent was the result of reducing the diameter of some of the lengths of sewer by one or two increments.

3.4 A more general approach to the determination of cost savings, was adopted by Harrison (8), who looked at the effect of overall ground slope and of maximum design discharge, on the cost of a sewerage scheme. In the hypothetical scheme that was considered in the analysis, it was assumed that all the pipes in the system were at the same gradient throughout and that the relative length of the pipes forming the system conformed to a distribution that had been derived previously from an analysis of several sewerage systems (9). The costs used in the analysis were the same as those that were used in the Ipswich study.

3.5 Estimates of the costs of schemes having outfall discharges of 4, 2 and 0.5 m^3/s for ground slopes of 0.01 (1/100), 0.02 (1/50), 0.05 (1/20) and 0.10 (1/10) were made for the two design conditions; in one the maximum velocity was restricted to 3.66 m/s and in the other there was no limit on the maximum velocity. The roughness height of the sewer was assumed to be 1.5 mm, equivalent to a normal slimed condition.

3.6 The conclusions from this analysis were very similar to those from the Ipswich Study. It was shown that the savings in cost by removing any limit on the velocity could be significant; they increase as the ground slope increases, and as the maximum discharge in the system increases – although the savings do not increase significantly for discharges greater than 4 m^3/s. The following table shows the percentage savings that result from removing the velocity limit.

Ground slope	Maximum discharge in system m^3/s	Maximum velocity in systems without velocity limitation m/s	Cost savings (as per cent of costs of scheme with velocity limit)
0.01	0.5	2.2	0
	2.0	3.0	0
	4.0	3.5	0
0.02	0.5	2.9	0
	2.0	3.8	1
	4.0	4.6	3
0.05	0.5	4.1	4
	2.0	5.7	10
	4.0	6.4	12
0.10	0.5	5.1	22
	2.0	6.9	26
	4.0	9.6	28

4 OTHER ASPECTS OF HIGH VELOCITIES

Although there is evidence that sewers designed without any limit on velocity do not give rise to serious problems, there are factors other than erosion that the drainage engineer should consider when designing such a scheme. The principal ones are as follows:

Energy losses 4.1

The normal practice when designing sewerage schemes appears to be to neglect losses at bends and junctions because they are usually small. However when the velocity is high, it is no longer possible automatically to neglect them. Although the form losses as a proportion of the total energy losses in the system may not change, whatever the velocity in the sewers, nevertheless they are significant in absolute terms at high velocities, because the freeboard in the manholes limits the amount of backing up that can be tolerated before they start to overflow. For example, if the head loss at a 45° open channel bend (such as occurs in a manhole) is $0.05\ v^2/2g$, this represents a loss of 0.003 m at a velocity of 1 m/s, 0.01 m at 2 m/s, 0.04 m at 4 m/s and 0.09 m at 6 m/s. Thus although the energy loss may be ignored when the velocity is 1 m/s, it is no longer possible to do so when the velocity is 6 m/s. Similar considerations apply to junctions.

There is not a great deal of information available about energy losses at open channel bends and junctions, particularly for channels of circular section, and for high velocities.

Safety chains when left in place across the sewer are other sources of energy loss that are not considered in the design of sewerage schemes and, again, there does not appear to be any information to help the designer. In order to determine how significant these losses might be, the energy losses were calculated assuming a drag coefficient of 1.2 for a chain consisting of links 4.5 cm long, 2.5 cm wide, made from 4 mm diameter bar suspended across a square channel (to simplify the computations), 0.3 m wide and 0.3 m deep. If the chain is made from larger diameter bar, the losses will be greater. A disadvantage of a safety chain is that, when left in place, it tends to catch floating rubbish, which greatly increases the effective diameter of the chains; for this reason, the calculation of energy losses was repeated assuming that the chain was equivalent to a solid cylinder of 2.5 cm diameter. The following table shows the energy losses produced for various conditions of flow; it is emphasised, however, that the calculation is only qualitative.

Velocity (m/s)	Head loss (m)	
	Chain unblocked	Chain blocked
1	0.001	0.002
3	0.02	0.05
6	0.07	0.19

As things stand at present, insufficient data are available to enable the engineer to compute all the energy losses in high velocity open channel flow; some data and additional references are available in Chapters 16 and 17 of (10) and Chapter 7 of (11). There is much more data available for the conditions when the sewers are flowing full (12).

Standing waves 4.2

A sewer that is designed to run full, will nevertheless operate for a considerable part of the time in a part-full state. If the velocity is high, it is quite likely that the Froude number

(ie $\dfrac{v}{\sqrt{gA/B}}$

where
v = velocity
g = gravitational acceleration
A = area of flow
B = water surface width)

will be very close to, or will be greater than 1. In this case any changes in the boundary geometry such as bends, junctions and manholes, will produce disturbances in the flow such as stationary waves, which can cause large local increases in the depth of flow. In some circumstances these surface waves will not have any serious consequences, because there is sufficient freeboard in the sewer to accommodate them: however, in other cases they could lead to intermittent choking of the pipe and instability in its mode of operation. Further information is provided in chapters 16 and 17 of (10) and Chapter 7 of (11).

Cavitation 4.3

When the velocity of flow is large, small discontinuities in the boundary geometry will produce local accelerations, and hence low pressure areas. If these pressures are sufficiently low, small vapour pockets will be created, which will move downstream with the flow, eventually to collapse in areas of higher pressure. The implosive collapse of these vapour pockets gives rise to very high intensities of pressure on the boundary, which can eventually cause the surface to fail. This process is called cavitation and is a feature of both pressure flow and open channel flow; there are numerous examples to be found in the literature, of the severe damage that has been caused, particularly in hydro-electric schemes, where large velocities are commonly experienced. More information is to be found in (13) and (14 – which also contains a full bibliography).

In order to prevent cavitation from occurring, it is essential that the surfaces of the conduits should be smooth and without any boundary discontinuities. The larger the discontinuity, the lower the velocity at which cavitation will occur. For example, with a velocity of 30 ft/s (9.15 m/s) and a depth of flow of 1.5 ft (0.4 m) cavitation will start if there is a joint discontinuity of 0.5 in (12.7 mm): for a velocity of 52 ft/s (15.9 m/s) and the same depth of flow, a discontinuity of only 0.06 in (1.5 mm) will cause cavitation.

Aeration 4.4

A feature of high velocity open-channel flow is the air that it entrains, producing a characteristic white water surface, and a depth of flow greater than that predicted by the uniform flow equations. The amount of air that will be entrained is a function of discharge, and channel geometry; as a rough guide, a velocity of 6 m/s has been quoted (10, p33), although an alternative expression for the velocity at which the amount of entrained air starts to become significant is $v = \sqrt{5gR}$ where g = gravitational constant, and R = hydraulic radius (15).

A useful summary is given in Chapter 6 of (11), and sufficient information is given to enable the depth of the aerated flow to be estimated.

As well as entraining air in the body of the flow the fast moving water surface will also drag the air above it, along the sewer. If the air is removed from the sewer, by this process, at a faster rate than it can be supplied through connections to atmosphere, the air pressure in the sewer system will become sub-atmospheric and on a foul sewer there is the possibility that the water seals on siphon traps could be broken by the pressure differential that would have been created. It is not known whether this is a problem.

Some research on the air demand of a fast flowing free water surface has been done, mainly in connection with the air demand of sluices in hydro-electric schemes (16). The air demand has been expressed as a function of the Froude number of the flow and the roughness of the channel. It may thus be possible to determine the size of air vents required to satisfy the air demand and thus prevent sub-atmospheric conditions from occurring.

Energy dissipation 4.5

This is much more of a problem with high velocity flow that it is with low velocities. However a great deal of work has been done on methods of dissipating energy and design data are readily available in the literature (10,11,17, all of which contain useful additional references). In order to be able to use these data, however, the designer needs to be familiar with the various longitudinal water surface profiles that can occur and should be able to make qualitative predictions of the profile that will occur in given situations – the references previously quoted all give guidance on this aspect.

If high velocity flow is discharged into a natural water-course, measures must be taken to prevent scour from occurring in the water-course (18,19).

Structural problems 4.6

High velocities will increase the dynamic forces acting on a sewer, particularly the lateral forces at a bend. For a given angular change of direction, the lateral force is proportional to v^2: thus an increase in velocity from 1 to 5 m/s will give a twenty-five fold increase in the lateral force. These lateral forces will be opposed by the passive earth pressure and by the frictional resistance to sliding of the bedding. The following table shows the effect of pipe diameter, bend radius and velocity on the horizontal bearing pressures at a 90^{0} bend: the pipe is assumed to be flowing full and the effect of any manhole on the distribution of the horizontal forces is not taken into account.

Diameter (mm)	Velocity (m/s)	Bearing pressure N/m^2	
		Radius 0.8 m	Radius 1.75 m
225	1	200	90
	5	5000	2250
	10	20000	9100
500	1	450	200
	5	11050	5050
	10	44200	20200
1000	1	900	400
	5	22100	10100
	10	88500	40400

If the ground passive pressure is in the range 40 000 to 140 000 N/m^2, which appears to cover typical values for clay and granular material, it appears that high velocities will not usually produce any structural problems. However, as an additional safety factor, (if a manhole is not constructed) it would be possible to provide an effective anchor block by surrounding the pipe with concrete, extending over the full width of the excavated trench, before backfilling is carried out. By this means no reliance need be placed on the compaction of the backfill alongside the pipe for resisting horizontal movement.

Safety 4.7

Safety provisions need to be planned with particular care wherever high velocities are expected to occur. A velocity of 4 m/s is equivalent to a pressure head of 0.8 m, a velocity of 6 m/s is equivalent to a pressure head of 1.8 m: anybody working near a sewer in which such velocities occur, would not be able to maintain a foothold if he fell in and would very easily be swept away. The recommendations of CP 2005 (2) for deep manholes, could be applied equally well to manholes on sewers where the velocity is high. In particular the provision of landing platforms, safety chains, and safety rails (par 6.1.2.1) and the utilisation of side entrance manholes, (par 6.1.3.3) are relevant.

5 FIELD EXPERIENCE OF HIGH VELOCITIES IN SEWERS

Selected members of the Standing Committee and a number of Water Authorities were asked whether they imposed upper limits on flow velocities in sewers, whether they had any sewers with a flow velocity greater than 3.66 m/s and whether they had experienced any problems with sewers flowing at high velocities. Ten written replies were received.

Of the replies received only one, a Water Authority, imposed an upper limit for velocity. This was imposed entirely for safety reasons. The limit imposed varied according to diameter, type and depth of flow in the sewer under normal conditions. Most other replies mentioned the safety aspects that must be considered with high velocities in large diameter sewers.

One Authority reported an incidence of erosion in a large diameter brick sewer laid at a gradient of 1 in 2. Apart from this single incident, erosion does not appear to be a problem even with velocities of 7 m/s – 8 m/s.

The hydraulic problems at entrances and exits and the need for energy dissipation devices were mentioned in several replies. In particular, the problems of steeply graded sewers flowing part-full, in the super-critical state, discharging into a flatter sewer in which the flow conditions are sub-critical were mentioned. In such cases a hydraulic jump occurs in the junction manhole and rapid wear of the manhole fabric takes place. The wear is thought to be caused by grit and other debris in the flow.

Two of the replies suggested that high velocities could result in the release of hydrogen sulphide and hence lead to other problems.

One reply suggested that the entrainment of air at high velocities could significantly increase the depth of flow in a sewer.

A similar survey was carried out by the Department of the Environment in 1974 (2). Of the 200 replies received from local authorities, water authorities, consultants and contractors, 4 per cent quoted a maximum permitted gradient (usually 1 in 10): however 55 per cent of the replies did not stipulate any limit on maximum velocity and quoted values ranging from 2 to 15 m/s.

6 CONCLUSIONS

The use of high velocities in sewers introduces considerations that are not normally encountered in the design of drainage systems. There is information available on some of these aspects, viz cavitation, energy dissipation, structural stability, safety; on other aspects, viz energy losses, standing waves, aeration, there is sinsufficient information, to allow the designer to cope with part-full and pipe-full conditions, both of which must be considered at the design stage. The part-full condition is important not only because it occurs more frequently than pipe-full, but also because surface waves and aeration will then be a feature, and these two factors could have a significant effect on the flow; in an extreme case they could produce an unstable mode of operation.

7 RECOMMENDATIONS

Further research work is clearly necessary, but before embarking on this, two preliminary steps are necessary:

a) a literature survey to determine how much information is already available that is relevant to the particular needs of the engineer designing sewerage schemes;

b) monitoring the performance of existing sewers in which high velocities occur, in order to determine how their performance is being affected by the aspects discussed in Section 4. The criteria for selecting the sewers for study should be high velocity, presence of bends, junctions and changes of gradients.

Once these two preliminary studies have been completed, it should be possible to define a research programme more clearly. At the present time it appears that further research will be required on energy losses at bends and junctions in open channels of circular section, on standing waves in open channels of circular section, and possibly on air demand and aeration of flow.

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