Paper presented at the 35th International W062 Symposium on Water Supply and Drainage of the Conseil International du Bâtiment (CIB) W062, held in Düsseldorf, Germany, 7−9 September 2009.

Designing sewers for reduced wastewater flows

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Abstract

There is increasing concern that reduction of wastewater flows arising from intensive water conservation and demand management may result in an increase in blockage and maintenance requirements for sewerage systems. A design methodology, developed primarily to reduce the cost of providing sewerage services to poor communities, has been demonstrated to function well with very low wastewater flows. It is proposed that a demonstration project be developed applying these principles to the design and construction of sewerage for a new housing development that incorporates a high level of water conservation. The ultimate objective would be to gain acceptance for a simpler and more rigorous sewer design methodology that can be applied to any flow regime regardless of the wastewater flow per connection.

Keywords

Sewer design, water conservation, boundary shear stress, simplified sewerage.

1 Introduction

Conservative assumptions and robust construction have until now provided a fairly reliable and durable solution to the sanitation requirements for a huge number of towns and cities. Generously sized pipes and robust construction have permitted huge increases of flow and expansions in the areas and numbers of properties served, but there is a new consideration that must now be taken into account: reducing wastewater flow. Scarcity of water resources and the possibility of climate change radically affecting rainfall distribution are motivating demand side measures to curb water demand so that future we may find ourselves in the position of having to anticipate reducing flows instead of having to make allowances for future increases. In addition the move away from combined sewers will remove the additional flow from stormwater that may provide periodic flushing of solids from the system.

The prospect of reducing sewage flows and changes in sewage composition as a result of water conservation gives rise to concerns over the effects that this might have on the sewerage system and sewage treatment.

The British Environmental Agency commissioned a study, *Less Water to Waste* (Drinkwater, Chambers and Waylen, 2008), which concludes, among other things, that design methods will require revision to take account of reduced wastewater flows.

In the UK sewerage design is governed by a number of documents, principally a standard, a code of practice and building regulations. The stipulations of these documents are not entirely consistent and there is a fourth report, *Design of Sewers to Control Sediment Problems* (Ackers, Butler and May, 1996) giving additional recommendations that are intended to minimise the problems caused by sediment in sewers. A review and revision of the sewer design practices is therefore justified, if only to clarify and simplify the process.

This paper proposes a methodology for designing sewers to account for reduced flows and a strategy for testing this approach.

2 Objectives for a revised sewer design methodology

Any sewerage design methodology has to address the three basic requirements of:

- Hydraulic capacity;
- Transport of solids; and
- Prevention of blockage

In addition it would be worthwhile establishing the principles that any methodology should be as simple as possible by setting values for a minimum number of parameters and that, if possible, the performance of sewers under conditions of reduced wastewater flows shall be no worse than sewers designed by established methods and experiencing typical existing flow rates.

2.1 Hydraulic capacity

The hydraulic capacity of a pipe conveying liquid by open channel flow are the pipe diameter, gradient and the maximum permitted depth of flow, $(d/D)_{max}$. Generally the depth of flow is limited to 0.75 or 0.8 of the pipe diameter to permit ventilation above the liquid surface and to provide an additional factor of safety against surcharging. There does not seem to be any reason to depart from this practice in devising a new design approach.

2.2 Transport of solids

The transport of sediment must be considered separately from the transport of gross solids as the mechanisms are different. Sediment consists of small particles that are transported in suspension, as a bedload close to the invert of the sewer, or deposited as a bed. The requirement for sediment transport has generally been accommodated by using a concept of a self cleansing velocity.

An alternative criterion, boundary shear stress, has been proposed as a means of ensuring that sewers are capable of transporting sediment. The average boundary shear stress is the average shear stress exerted on the sewer wall by the moving liquid and is given by the expression:

$$\tau = \rho g R i \tag{1}$$

Where τ is the average boundary shear stress, ρ is the density of the wastewater, g is the acceleration due to gravity, R is the hydraulic radius, and *i* the slope.

Although not the first person to advocate the use of boundary shear stress in sewer design, Yao (1974) appears to have produced the first design procedure using this concept. Yao noted that experimental results showed that the velocity required to transport low concentrations of sand through pipelines varied as the square root of the pipe diameter and so a single value of self cleansing velocity could not be applied in all cases, whereas a single value for boundary shear stress should be valid for all pipe diameters, other factors such as sediment composition and load remaining unchanged.

Boundary shear stress is also the basis of the recommended procedures presented in Ackers, et al. (1996). This report, published by the Construction Industry Research and Information Association had the objective ' . . . to develop a standard methodology for the hydraulic design of sewers to control sediment problems, and to produce from it appropriate guidance on the subject for design engineers.' In addition to reducing sediment problems in sewers, the approach was expected to produce more economic designs for small diameter sewers which tend to be over-designed using a single value for self-cleansing velocity.

It would therefore seem that any future design methodology for sewer design should accept the basic proposal put forward by Yao and include a minimum value for boundary shear stress (τ_{min}) and have no need of any consideration of velocity.

2.3 Prevention of blockage

There has been a significant amount of research into the transport of larger solids, particularly related to the design of drainage within buildings, see for example Wise and Swaffield (1995). This has concentrated on examining the distance that test objects are transported by a standard pulse of water, designed to simulate the discharge from a WC, in pipes of differing diameter and gradient. The experimental results clearly show that solids are transported further in smaller pipes than larger ones and in pipes with steeper gradients than ones with less slope. This is explained by the concept of damming of the water flow behind the object and the resulting forces overcoming friction and moving the object forward at each successive passing wave.

One way to ensure that the pipe diameter is not too large is to ensure that a minimum depth of flow $(d/D)_{min}$ is achieved at the daily peak flow and that the smallest available pipe size is used that will accommodate the anticipated maximum peak flow. In practice this may well be smaller than the minimum size permitted under sewer design regulations, which in some places is 200 mm or even larger.

This assumption is also supported by findings of an investigation into the causes of sewer blockage in the UK (Lillywhite and Webster, 1979), which concluded that the main factors contributing to blockage were the degree of utilisation, which is equivalent to the depth of flow, and defects in construction.

2.4 Sewer gradient

The same study found that sewer gradient appeared to have little effect on the rates of blockage, which may sound surprising, but one length of 100 mm diameter sewer that was investigated was found to have a gradient of 1:1200 and to be operating without problems.

A minimum value for gradient can be determined using the set value of boundary shear stress and minimum depth of flow, however, it is difficult to determine the flow rate to use for the upper reaches of sewers where there are few connections. The average flow will be very low and even a high value for peak flow factor will not yield a useful result. A valid approach would be to use a value for the minimum peak flow that corresponds to the peak flow from a single connection. This would be equivalent to the discharge from a single WC. This concept is included in the National Appendix to EN 752 (BSI, 2008) which states a minimum value for flow should be taken as 1.6 l/s.

This is in contrast to current UK practice where minimum gradients are stipulated for different pipe diameters and flow rates. Also for a 100 mm drain the number of connections permitted is limited to 10, which is contrary to the findings of Lillywhite and Webster (1979) that the flow should be maximised.

In conclusion, the parameters that should be considered to minimise sewer blockage will include a minimum value for the relative depth of flow $(d/D)_{min}$, a minimum pipe diameter, D_{min} and a value for the minimum flow rate, q_{min}. It is also is important that the minimum pipe diameter that will meet the hydraulic requirements is selected to ensure that the level of utilisation is maximised.

The only other requirement to explicitly determine the required pipe diameter and gradient for a given flow regime is the peak flow factor F_p. This should be determined as accurately as possible, from measurement of flow rates in similar sewer lengths if possible. Because of the need to maximise the level of utilisation, there should be no hidden partial safety factor incorporated in this value to account of unforeseen development or infiltration. These must be explicitly estimated and incorporated into the value for estimated future flow.

2.5 Potential design methodology

The proposed methodology will therefore depend on setting values for 6 parameters discussed above and developing the necessary design equations based on a standard pipe flow formula. This may taken as the Manning-Strickler equation using the commonly adopted value for n of 0.013 for slimed sewer pipes, regardless of the material. The extra complication introduced by using more accurate flow formulae, such as Colebrook White, is not justified, but this would be an equally valid approach.

As noted above, the use of boundary shear stress for sewer design has been advocated for over 35 years, but has not gained wide acceptance. Before making such a major change in design approach, it would be useful to have some demonstration of the effectiveness of the methodology and experience of its widespread application. Fortunately there is such evidence available through the development of a design philosophy in Brazil that substantially reduces the costs of providing sewerage so that low-income households can afford water borne sanitation.

3 Simplified Sewerage

The simplified sewerage concept was originally developed in the northeastern Brazilian state of Rio Grande do Norte as a means of providing an affordable water borne sewerage service to low income housing areas, both planned and un-planned. The key to this approach is that the hydraulic design is rigorous and the system is hydraulically as efficient as possible.

Design was based on a self cleaning velocity of 0.5 m/s and a minimum peak flow of 2.2 l/s. This resulted in a minimum gradient of 1:167 for a 100 mm diameter sewer (de Andrade Neto, 1985; UNCHS, 1986). Because one of the major cost saving strategies was to locate sewers though private land within the housing block, it was known as condominial sewerage.

Other state water companies in Brazil quickly adopted this approach and to suit local conditions constructed sewers beneath sidewalks or front gardens as well as in-block. At the same time the design basis was changed to one based on boundary shear stress, known as tensão trativa (tractive tension) (Machado, Neto and Tsutiya, 1985). The simplified sewerage concept has been incorporated in the Brazilian Sewer Code (ABNT, 1986) and has been applied in other countries, mainly in south Asia and Latin America.

3.1 Design equations

The values for the parameters identified above and as applied in Brazil are:

Minimum boundary shear stress	τ_{min}	1 N/m^2
Minimum proportional depth of flow	$(d/D)_{min}$	0.2
Maximum proportional depth of flow	$(d/D)_{max}$	0.8
Minimum peak flow rate	q_{min}	1.5 l/s
Minimum pipe diameter	D_{min}	100 mm
Peak flow factor	F_p	As measured, typically 1.8

The minimum diameter suggested here is for collector sewers, however, 75 mm may be more appropriate for the property connection, but this has seldom been applied, largely due to the lack of drainage fittings for 75 mm pipe.

Based on the Manning-Strickler equation, design equations for minimum gradient and pipe diameter can be derived, as shown in Bakalian, Wright, Otis and Azevedo-Neto (1994), Mara (1996) and Mara and Broome (2008). The minimum gradient can be determined from of flow, τ_{min} and $(d/D)_{min}$:

$$i_{min} = [(1/n)k_a k_r^{-2}]^{6/13}(\tau_{min}/\rho g)^{16/13}\, q^{-6/13} \qquad (2)$$

where:

$$k_a = \frac{(\theta - \sin\theta)}{8} \quad \text{and } k_r = \frac{1}{4}\left(1 - \frac{\sin\theta}{\theta}\right)$$

θ angle subtended at the centre of the sewer by the wastewater surface (radians)
n Manning's roughness coefficient (usually taken as 0.013)

Substituting the values commonly used in Brazil this simplifies to:

$$i_{min} = 2.33 \times 10^{-4} q^{-6/13} \qquad (3)$$

Similarly the pipe diameter required for a given maximum or minimum flow rate, gradient and proportional depth of flow can be determined:

$$D = (nq)^{3/8} k_a^{-3/8} k_r^{-1/4} i_{min}^{-3/16} \qquad (4)$$

The minimum diameter is determined from the maximum peak flow and maximum proportional depth of flow, taking the next larger size of commercially available pipe. The maximum diameter is determined from the minimum peak flow, which will usually be the initial condition with only partial development of the catchment, and the minimum proportional depth of flow.

It can be seen that the design equations lead directly to explicit solutions for minimum gradient and pipe diameter and so are relatively simple to apply. However, a key advantage in developing the equations governing hydraulic design from set values for a minimum number of parameters is that the design is consistent. Once the appropriate values are selected for those parameters, all aspects of the hydraulic design are defined and there is no need for any of the empirical or arbitrary limits on gradient or numbers of connections that are common in self cleansing velocity design procedures. If it is found, for instance, there is deposition of sediment, it would be a simple matter to adopt a higher value for boundary shear stress, without any need to adjust any of the other parameters.

For detailed description of the application of simplified sewerage principles see Mara and Broome (2008), which includes instructions for a simple design template for selecting pipe diameter and gradient.

3.2 Applications of simplified sewerage

Simplified sewerage was developed to reduce the cost of water borne sewerage to affordable levels and the cost is typically in the range of half that of conventionally designed and constructed sewerage. While most water companies in Brazil have only applied simplified sewerage principles to low-income areas, the state water company serving the Federal District of Brasilia is using the approach in high income areas as well (see Fig. 1).

In many of the projects where the simplified sewerage approach has been adopted, the hydraulic loadings have been very low. Often the WCs connected will be of the pour flush type, in that they are not provided with a flushing cistern and the flushing water is carried to the toilet and poured into the pan. In many cases the water used is sullage from other uses and so the wastewater flow is even lower than would be expected from the 1.5 to 2 l used per flush (see Fig. 2).

Figure 1: Simplified sewerage being installed at the back of the pavement in Brasília

Figure 2: Pour-flush squat-type WC

In Orangi, a district of Karachi, Pakistan, simplified sewerage was introduced successfully in an area where the water consumption was measured at the start of the project as only 27 lcd obtained from intermittent piped supplies and vendors. Admittedly the gradients are probably higher than in most simplified sewerage project areas, but the success shows that sewerage will function with very low wastewater flows.

4 Design for low flows in industrialised countries

Simplified sewerage is a mature technology that has been applied in various parts of the world with a great deal of success. Admittedly there have been failures, but under similar conditions, conventional sewerage systems also often fail.

It would therefore seem reasonable to assume that a design methodology that can produce successful sewerage systems with very low flows in developing countries could also be applied in other contexts, such as in industrialised countries where there are concerns about reducing wastewater flows. However, there are serious obstacles to overcome. In developing countries there is often strenuous opposition to adopting alternative design criteria that may be seen as inferior.

The idea that smaller pipes are less likely to block than larger ones seems counter-intuitive to many people and so the need to reduce the minimum sewer diameter is probably the greatest impediment to the widespread adoption of the simplified sewerage design approach. An example of this occurred in Faisalabad, Pakistan where the minimum sewer diameter was maintained as 225 mm (9 inches) (Khatib Alam and Parkinson, 2002), when a key feature of simplified sewerage is that pipe diameters should be selected to maximise utilisation and so a 100 mm, or at most 150 mm diameter should have been selected.

Given that in the UK rules of thumb from more than a century ago, Maguire's Rule for example, are enshrined in standards and codes of practice (BSI, 2008; WRc, 2006) and the European standard is based on self-cleansing velocity approach, it may prove difficult to gain acceptance of alternative design methodologies and philosophies.

4.1 Additional supporting evidence

In addition to the success of many simplified sewerage schemes in developing countries, there is evidence from the USA and the UK that there is some convergence in approach and some elements of simplified sewerage design are already in use.

In the US state of Nebraska there has been a long and successful history of using ‘flat grade sewers’. Due to the typically flat topography and high water tables in the state, 150-mm and 200-mm diameter sewers have been laid at gradients as flat as 1 in 900, without any ‘unusual’ maintenance requirements (Gidley, 1987).

Mara and Broome (2008) show that the simplified design method of Ackers et al. (1996) gives very similar results for the minimum gradient for small diameter sewers and drains when compared with the simplified sewerage design procedure, as applied in Brazil.

The UK National Annex to EN752 (BSI, 2008) contains a provision that is equivalent to the minimum flow criterion of simplified sewerage, that the minimum flow for the design of drains and sewers serving small numbers of dwellings should be taken as 1.6 l/s (i.e., close to the value of 1.5 l/s used in Brazil). This is not included in the code of practice (WRc, 2006) which instead stipulates average flow rates and implicitly prescribes a very high peak flow factor of 6.

Pressure from housing developers to reduce the cost of construction of sewerage has led to the substitution of sealed access fittings for manholes and also the relatively recent relaxation of some rules that govern the number of connections permitted on 100 mm diameter drains (DEFRA, 2002). These developments represent cautious moves towards some aspects of the simplified sewerage design philosophy.

4.2 Research versus demonstration

The basis of the UK Environment Agency's report on the impact of low flows on sewerage systems (Drinkwater, 2008) was to seek evidence from existing systems where flows are reducing and so failed to identify the development of simplified sewerage as a methodology that has been shown to operate in areas with very low water consumption rates.

As a result of this, the report recommends a variety of investigations as a necessary input to revising design methods, but does not give much indication of what the '… practical investigations into the effects of reduced WC flush volumes on the parts of the drainage system most susceptible to blockages due to low flows …' might actually achieve (Drinkwater et al., 2008). Nor does the suggested rig based testing hold much hope of simulating actual conditions in the upper reaches of drainage systems where flows are intermittent and solids are regularly stranded. It therefore follows that the only way to really test the proposed approach is to construct an actual sewerage system serving an area where all connections serve properties with very high levels of water conservation. This is, after all, the way that current design standards were developed.

Since there is likely to be resistance to the idea of a new design methodology, a convincing demonstration will be required to convince sceptical engineers, other professionals and members of the public. There will undoubtedly be an unwillingness to abandon all the accumulated experience of traditional practice and there is also a huge difference in the cultural and hygiene behaviour between industrialised countries and those where simplified sewerage has been operating successfully.

If such a drainage system is to be constructed, it will be necessary to identify a type of development where the water conservation objectives are combined with a sufficiently extensive drainage system that would form a suitable pilot area for the project. One important aspect of prestige 'low carbon' and 'zero carbon' housing developments is water demand management. This would make such developments an ideal testing ground for alternative approaches to sewer design.

4.3 Obstacles to developing a pilot scheme

There are clearly going to be a lot of obstacles to using a new design basis, not the least of which is that EN 752 (BSI, 2008) explicitly states that self cleansing velocity methods should be used (see Section 9.6.3). However Section 8.7.3 does state that 'Drains and sewers shall be designed to provide sufficient shear stress to limit the build up of solids …' Local planning laws, building regulations and water company policy are also almost certainly going to be an impediment to a radical departure from established practice. The successful development of a pilot scheme is therefore going to require a high level of commitment from the developer and its financiers, political support and a flexible approach by all the regulatory bodies involved.

The duration required for such a demonstration project to yield results and the possible longer term consequences, of increased maintenance requirements for example, means that it will need significant resources in addition to those required for actual construction.

4.4 Possible experimental design

Any demonstration project would need to demonstrate that:

- The system works as well, or better than existing standard practice;
- The design methodology is simple to apply and the resulting sewerage system is simpler, or is at least no more difficult to build than a conventional one; and
- The resulting sewerage system will be more economic.

A possible sequence of activities could include a review of the performance of simplified sewerage systems, development of standards for the UK that have the potential to meet the expectations of water companies and regulatory bodies, but without compromising the principles of simplified sewerage, comparison of costs for conventional and simplified sewerage systems and finally the construction of a sewerage network based on the proposed methodology.

Assessment of the success of the design would be based on monitoring of water consumption and sewage flows, requirements for maintenance, the CCTV inspection of sewers. It is extremely improbable that suitable data will be available to compare the experimental systems with conventionally designed sewers. Not only is comprehensive data on sewer blockage, routine cleaning and other maintenance unlikely to be available for comparable sewerage networks, any available data would be difficult to correlate with water consumption and wastewater flows. It would therefore be necessary to include within the demonstration scheme a control area designed strictly in accordance with established practice, codes and standards.

The outputs from the demonstration project should include a number of individual pieces of academic research and a summary of the development of the project and research findings. In addition there should be a draft standard for sewer design that would hopefully be suitable for designing sewerage both for areas with conventional plumbing fixtures and average wastewater generation rates and for areas where high levels of water conservation and greywater recycling are implemented.

4.5 Risks

There are a number of potential risks that will need to be addressed before a developer and other participants in a demonstration project are likely to be willing to proceed. These include:

- Failure to obtain the necessary waivers or derogations of regulations and standards;

- Opposition from water companies (adoption is not likely to be possible in any case);
- Possible additional maintenance requirements;
- Difficulty of selling an experimental system to potential residents; and
- Resourcing a rather long term project.

However, with sufficient support from agencies responsible for water resources management, housing and infrastructure provision, it should be possible to reduce these risks to acceptable levels and implement a successful project.

5 Conclusions

A methodology developed in Brazil to provide sewerage services to low income communities has been proved to work well with low wastewater flows and which has been successfully implemented in a number of countries. There seems little reason to doubt that this approach, known as simplified sewerage, could also be applied in industrialised countries to accommodate reduced wastewater flows arising from water demand management and greywater recycling.

Rather than continue to promote research through laboratory testing and small scale studies of existing conventional sewerage systems, a demonstration project would be far more effective in influencing sewer design methods. Although promoting a demonstration project will be far more difficult than continuing individual small scale research projects, largely because of the scale necessary, it is probably the only way to effectively validate the design principles proposed.

Adoption of simplified sewerage design methods would greatly simplify sewer design by reducing the number of individual regulations and standards to a minimal set of parameters that define all aspects of hydraulic design.

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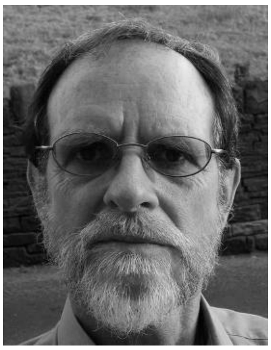

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