# Small diameter gravity sewers: self-cleansing conditions and aspects of wastewater quality

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**Abstract** The construction of conventional sewerage systems in small communities, with pipes laid on a uniform slope and manholes regularly spaced, is sometimes not economically feasible, because of the high costs of sewer installation. Under those circumstances, the small diameter gravity sewers (SDGS) have often proven to be substantially less costly than conventional sewers. Typically, in SDGS systems the wastewater from one or more households is discharged into an interceptor tank (or a single compartment septic tank). The settled effluent is discharged afterwards into small diameter sewers operating under gravity.

In this paper, special emphasis is given to the analysis of self-cleansing conditions and to the analysis of risks of sulphide generation and occurrence of septic conditions in SDGS systems. For the evaluation of the self-cleansing conditions, the critical velocity and the critical shear stress were computed according to the Shields equation. The forecasting of dissolved oxygen concentrations and sulphide build-up along the lines, for different flow conditions, was done running an established wastewater quality model.

**Keywords** Dissolved oxygen; interceptor tank; self-cleansing; settled sewage; small diameter gravity sewers; sulphides

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## Introduction

In small communities, conventional sewerage includes, in general, pipes with a minimum diameter, usually between 150 mm and 200 mm, laid on a uniform slope and manholes regularly spaced. Under certain conditions, the construction of conventional sewerage is not economically feasible because of the high costs of sewer installation. The collection system is the most costly component of conventional sewerage and it can became excessively costly in small communities where homes are typically scattered (Otis, 1981). It is known that in small scattered communities, namely of the south of Europe, conventional sewer systems serving populations below 500 habitants can cost more than USD1000 per habitant (Rocha and Marques, 1999).

The first small diameter gravity sewer system was constructed in Pinnaroo, South Australia in 1962. It was used as a solution to correct severe problems with failing septic tank systems. The small diameter gravity sewers, small collector mains (100 mm) laid on a uniform gradient sufficient to maintain only a 0.45 m/s flow velocity, were designed to collect the effluent from the existing septic tanks. This solution proved to be a more cost effective one then conventional gravity sewers – it has been estimated that construction costs were reduced by 30 to 65% (US Environmental Protection Agency, 1991). As a result, by 1986 over 80 schemes had been constructed in Australia. The largest scheme serves 4000 connections (Otis, 1996).

Experience with small diameter gravity sewers has been excellent and, as a result, design practices have rapidly evolved and have become less conservative.

In this paper, special emphasis is given to the self-cleansing requirements of unconventional small diameter gravity sewer systems (SDGS), taking into account the flow and the solids free nature of wastewater. Computations have also been done, running an established

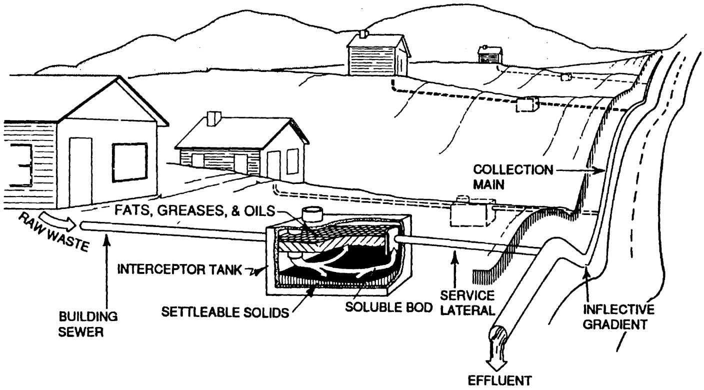


**Figure 1** Schematic representation of a small diameter gravity sewers system (adapted from US Environmental Protection Agency, 1991)

wastewater quality model, in order to investigate possible transformations along the lines (dissolved oxygen and sulphides concentrations) and to have an idea about risks of odour nuisance, toxicity and corrosion within the systems.

## General considerations about small diameter gravity sewer systems

Small diameter gravity sewer systems consist mainly in interceptor tanks and small diameter collection mains. Typically, this type of system includes house connections, interceptor tanks, service laterals, collector mains and appurtenances (cleanouts, manholes and vents), as illustrated in Figure 1. It may include lift stations at individual connections.

The interceptor tanks, located upstream of each connection, remove grease and settleable solids from the raw wastewater. This means that the sewerage system only receives the liquid portion of the sewage for conveyance, thereby permitting the use of smaller diameter collectors and eliminating the need to maintain good velocities.

Collector mains are usually laid on a uniform slope or even with flat or negative grades. These systems with inflective gradients, called variable grade systems, in which the sewers are allowed to operate in a surcharged condition, are becoming more common. This means that minimum velocities may be no longer an important design criterion – with the solids removed, the collector mains need not be designed to carry solids as conventional sewers must be.

SDGS can be cost advantageous over conventional gravity sewers specially under rocky conditions, due to the low depth of excavation, and in flat terrain or undulating topography areas, due to the fact that the line can be laid at relatively constant depth regardless of the natural grade (variable-grade gravity sewers). The only significant maintenance cost of SDGS is the interceptor tanks – each interceptor tank in the system must be pumped regularly (typically on 7–10 year cycles for residential connections) and the septage disposed of properly.

Small diameter gravity sewer systems have proven to be substantially less costly than conventional sewers. In many places, cost savings ranging from 20 to 50% have been reported (Otis *et al.*, 1996).

Nevertheless, when flowing in a surcharged condition, with alternating positive and negative slopes, it is supposed that the unconventional small sewer systems may present some difficulties, in respect to the fulfilment of self-cleansing conditions and the risks of occurrence of septicity and corresponding impacts on the environment (odour, toxicity and corrosion).

## Self-cleansing conditions in small diameter gravity sewer systems

### General aspects

Conventional sewerage design is based on achieving "self-cleansing" velocities during normal daily peak flow periods to transport any grit which may enter the sewer and scour grease and ressuspended solids that have settled in the sewer during low flow periods.

For self-cleansing evaluation, the general accepted standards often require a minimum critical velocity or a minimum critical shear stress.

According to ASCE (1982), the velocity required to transport sediments in pipes may be given by the following expression, developed by Shields:

$$V_c = \frac{R^{1/6}}{N}\sqrt{B(d_s - 1)D_S} \quad (1)$$

where

$V_c$ - self-cleansing velocity (m/s);

$R$ - hydraulic radius (m);

$N$ - Manning's coefficient ($m^{1/3}s^{-1}$);

$d_s$ - specific gravity of the particle (–);

$D_s$ - equivalent diameter of the particle (m);

$B$ - dimensionless constant (–).

The constant "*B*" may assume a value of about 0.04 to start motion of clean granular particles and of about 0.8 for adequate self-cleansing of cohesive material. Cohesion of deposit particles is perhaps the least known factor in determining scouring velocities. The silt-clay percentage of sewer deposits is typically low, and research in creek channels shows that if the silt-clay content is below 5%, critical shear stress is a function of individual particle sizes and is not significantly affected by cohesive properties. However, wastewater contains grease, oil and other organic materials. These materials, as well as the biological growth of slimes within the deposits, may increase cohesive properties of the sediments.

The average boundary shear stress on the wetted perimeter of the sewer is as follows:

$$\tau = w.R.S \quad (2)$$

where

$\tau$ – average boundary shear stress ($N/m^2$);

$w$ – specific weight of the water (9800 $N/m^3$);

$S$ – invert slope (–).

Assuming the Manning-Strickler expression, and taking into account expressions (1) and (2), it is possible to demonstrate that,

$$\tau_c = w.B(d_s - 1)D_s \text{ or} \quad (3)$$

$$\tau_c = w.R^{-1/3}.V_c^2.N^2 \quad (4)$$

where $\tau_c$ is the critical boundary shear stress ($N/m^2$) and the other terms are as previously defined. The critical boundary shear stress and the critical velocity are related by expression (4), the relationship depending on the hydraulic characteristics of the flow and on the specific weight of water.

The general accepted standard of a minimum critical velocity of 0.6 m/s, for the daily peak flow conditions, corresponds to a shear stress criterion between 1.5 and 2 $N/m^2$, for small diameter sewers (between 200 and 400 mm diameter) (Matos, 1992).

The consideration of a low critical shear stress, perhaps below 1 $N/m^2$, will be appropriate when wastewater contain only small-sized grit particles (1 mm maximum) and limited grit load, and when frequent self-cleansing velocity events occur (ASCE, 1989).

Shear stresses of 2 $N/m^2$ and higher could be appropriate for large-sized gravel material found in combined sewers and some sanitary sewers, principally where no frequent self-cleansing velocity events occur.

The size of the grit material to be moved is important. In sanitary sewers, the largest grit material is usually in the 1 mm to 5 mm range. For transport sewers where degritting facilities are provided upstream, the largest size of grit will depend on the type of grit removal facilities and their performance. Typically, grit removal facilities remove most particles greater then 0.2 mm (ASCE, 1989).

The material in wastewater can be classified by size and state as settleable, suspended, colloidal and dissolved. The size range for the various categories is somewhat arbitrary and is often related to the techniques used for their measurement. In practice, the solids in wastewater are divided into two broad categories: dissolved (including colloidal and small suspended particles below 0.0012 mm) and suspended, including settleable. The distinction is made using a glass fiber membrane filter with a nominal bore size of about 0.0012 mm (1.2 μ). Particles passing the filter are classed as dissolved (and colloidal). Particles in the size range from 1.2 to 10 μ are classed as suspended but not settleable. Particles with a size above 10 μ are usually classed as settleable (ASCE, 1989).

#### Self-cleansing conditions in small diameter gravity sewer systems

In SDGS systems the interceptor tank, placed downstream of the household, provides removal of grease and settleable solids from the raw wastewater. This means that the sewerage system receives the settled effluent with dissolved material, including colloidal and small suspended particles. Attending to the following considerations: (a) particles with a size above 0.01 mm are usually classed as settleable and (b) in designing grit chambers, the normal criterion is complete removal of particles with a size of 0.2 mm, it is reasonable, and conservative to assume that the sewage conveyed by SDGS systems only carries particles with sizes below 0.2 mm.

According to this, Figure 2 was computed based on Expression (3).

In this analysis, specific gravity of 1.2 was considered. This value relates to organic particles in wastewater. Constant "B" was considered equal to 0.05, 0.10 and 0.30. These values correspond to start motion of clean granular particles and to the existence of some cohesive material in the wastewater. The higher one relates to a situation where some aggregation of organic particles may take place into the sewer line, due to high detention

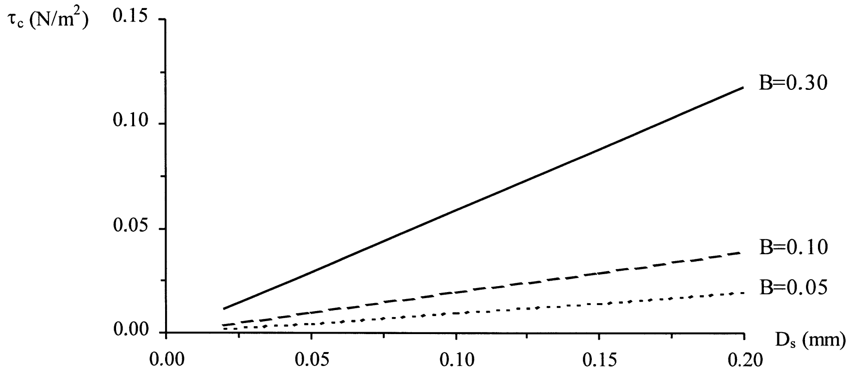


**Figure 2** Critical shear stress for *h/d*=0.5

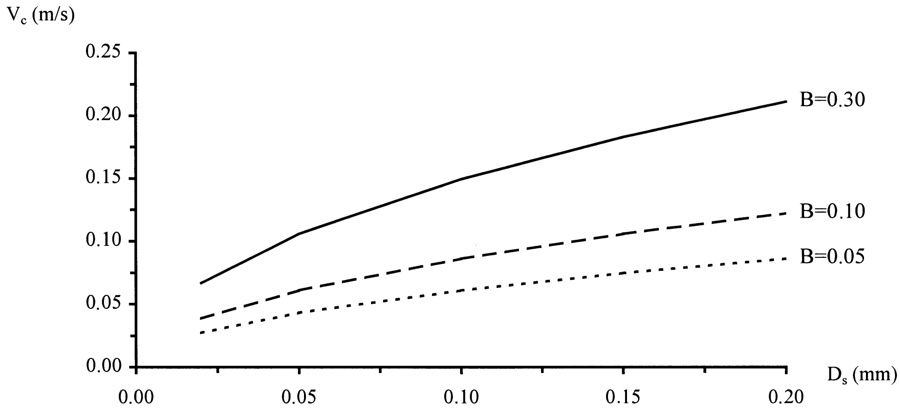


**Figure 3** Critical velocity for *h/d*=0.5; *d*=100 mm (*N*=0.013 $m^{1/3}s^{-1}$)



times. Figure 2 illustrates the lower values of the critical shear stress required to guarantee self-cleansing conditions in small diameter gravity sewers, when compared with the values computed for conventional gravity sewers. Indeed, for SDGS systems, and according to the conditions expressed, a critical shear stress value of 0.15 N/$m^2$ seems high enough to ensure self-cleansing conditions of the settled wastewater.

According to Expression (4), Figure 3 was computed. It relates to a 100 mm diameter sewer, flowing half full with a Manning`s coefficient of 0.013 $m^{1/3}$ $s^{-1}$. Generally, for a given sewer after some time in service, Manning's coefficient is approximately constant, not depending on the pipe material but representing slime build-up on the pipe walls. This coefficient will be on the order of 0.013 $m^{1/3}$ $s^{-1}$. A value of the Manning's coefficient of 0.015 $m^{1/3}$ $s^{-1}$ may be appropriate when significant slime growth is predictable.

## Dissolved oxygen and sulphides along the lines

### General aspects

During transport of wastewater in sewer systems, microbial processes proceed, which result in transformations of organic carbon and sulphur components (Nielsen *et al.*, 1992). These processes take place in the water phase, in the biofilm and in temporarily settled sediments. The dissolved oxygen (DO) concentration determines whether processes take place under aerobic, anaerobic or varying conditions, (Tanaka, 1998). In general, the determining factor in respect to the occurrence of sulphide is the dissolved oxygen balance (DO) in the stream. The concentration of DO in the bulk water is a result of a balance between microbial consumption processes, chemical processes and reaeration from the sewer atmosphere.

In the upstream reaches of wastewater collection systems, DO concentrations are in general relatively high and decrease with the distance travelled by the wastewater. Dissolved oxygen is increased primarily through reaeration at the stream surface and through turbulence induced by junctions, drops and hydraulic jumps (U.S. Environmental Protection Agency, 1985). Oxygen is lost through consumption by micro-organisms present within the stream and within the slime layer due to biochemical oxidation of organic matter. The extent of oxygen diffusion into the film is limited by the rapid oxygen utilisation by aerobic bacteria near the surface of the layer. Beneath the aerobic zone, anaerobic conditions may prevail and sulphides can be generated. For the sulphide formation within the slime layer a medium completely devoid of free oxygen or any other active oxidising agent is required.

Studies of sulphide production in gravity sewers and pressure mains have been carried out during the last 50 years, and several empirical equations or models for the prediction of sulphide build-up along the lines have been proposed (Pomeroy, 1959; Thistlethwayte, 1972; Boon and Lister, 1975; Pomeroy and Parkhurst, 1977; Hvitved-Jacobsen *et al.*, 1988 and Nielsen *et al.*, 1998).

In Matos (1992) is presented an integrated model, the AEROSEPT model, for the prediction of dissolved oxygen and sulphides in the sewage and hydrogen sulphide build-up in the sewer air. The reaeration process is based on Parkhurst and Pomeroy (1972), the DO consumption on U.S. Environmental Protection Agency (1985) and Matos and Sousa (1991, 1996). The sulphide generation is based on Pomeroy (1959) and Pomeroy and Parkhurst (1977). The description of the AEROSEPT model is presented elsewhere (Matos, 1992).

More recently, a process model description for wastewater aerobic/anaerobic transformations in sewers (WATS model) including reaeration and main aerobic and anaerobic processes in the bulk water phase as well as in the biofilm was established (Tanaka and Hvitved-Jacobsen, 1998). The integration of the aerobic/anaerobic carbon cycle and sulphide line in sewers made it possible to take into consideration integrated aspects of hydrogen sulphide and changing Chemical Oxygen Demand (COD) components in sewers, e.g. odour and sewer corrosion due to hydrogen sulphide and malfunctioning of advanced treatment due to input of low quality wastewater (Tanaka, 1998).

Although the environment of a sewer is highly dynamic and fluctuations in flow and pollutant concentrations over day and night may affect concentrations of DO and sulphides, case studies comparing the results predicted by sulphide generation with observed conditions in sewers establish the reliability of forecasting models.

The AEROSEPT model has been intensively applied, with promising results, to a lot of sewer systems (Matos, 1992 and Matos and Aires, 1994).

#### Calculations and obtained results

In this paper, the AEROSEPT model was run in order to investigate the potential risks of occurrence of septicity in SGDS systems flowing under surcharged conditions.

In Figure 4, dissolved oxygen (DO) and sulphides concentrations (expressed as $S^{2-}$) along a 200 mm diameter gravity sewer, laid with a constant slope of 0.005, are presented. The calculations were made running the AEROSEPT model for different flow conditions, $F_1$, $F_2$ and $F_3$ (corresponding respectively to relative flow depths of 0.500, 0.250 and 0.125), assuming a temperature of 20ºC, a $BOD_5$ of 400 mg/l and an initial DO deficit of 4.5 mg/l. The hydraulic characteristics of the flow were computed according to the Manning-Strickler equation.

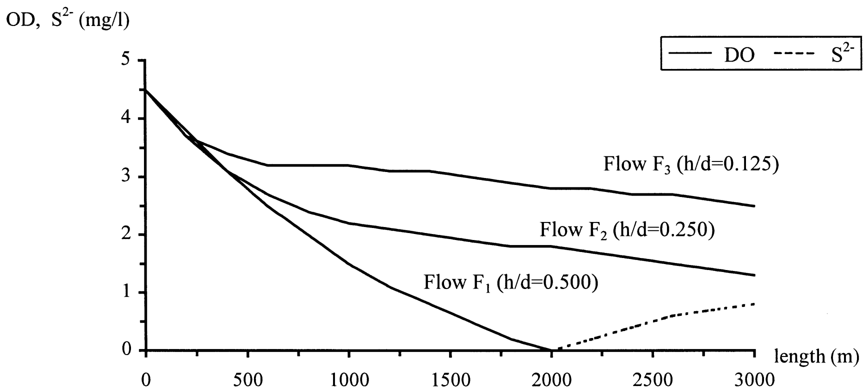


**Figure 4** Dissolved oxygen and sulphide concentrations along a conventional gravity diameter sewer ($d$=200 mm, $s$=0.005) for different flow conditions (relative depth of 0.125, 0.25 and 0.50)

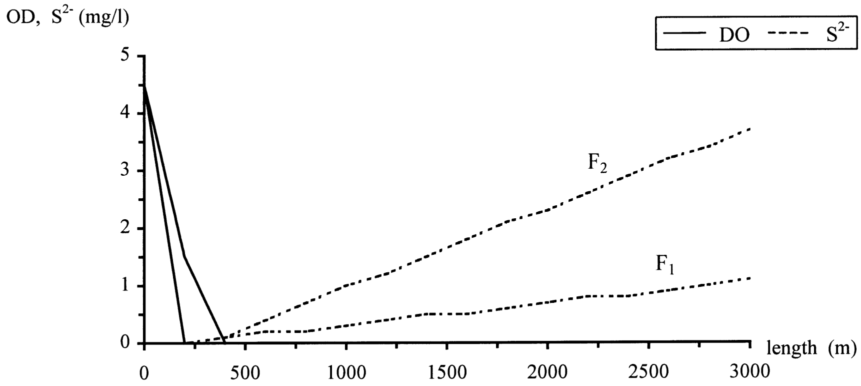


**Figure 5** Dissolved oxygen and sulphide concentrations along a SDGS (d=100 mm), in surcharged conditions, for different flow conditions (high flow, $F_1$, and lower flow, $F_2$)

In Figure 5 DO and sulphide concentrations along small gravity sewers under surcharged conditions are presented. Figure 5 concerns a 100 mm diameter. The calculations were made running the AEROSEPT model for two different flow conditions, $F_1$ and $F_2$, as previously defined. A temperature of 20ºC and an initial DO deficit of 4.4 mg/l were assumed. For taking into account the BOD removal in the interceptor tanks (or septic tanks) a value of 240 mg/l was considered in the calculations, instead of 400 mg/l.

According to the results obtained, for conventional gravity sewers of 200 mm diameter flowing less than half-full, no septic conditions will develop (specially for relative flow depths below 0.25; $h/d < 0.25$).

The effluent transported within a SDGS system is previously settled in the interceptor tank placed downstream of the household. This means that grease and settable solids are removed from the raw wastewater and that the sewerage system receives the settled effluent with a lower organic load. In this situation, the degree of biological oxidation that occurs within the stream will be relatively low, due to the lower concentration of organic matter. The risks of sedimentation and significant growth of slime layer are also low. Nevertheless, and because of the absence of reaeration and oxygen inputs, sulphide production may be significant in gravity sewers flowing in surcharged conditions, specially for the case of low flows and high travel times.

## Conclusions

In this paper, the self-cleansing conditions of unconventional small diameter gravity sewer systems (SDGS) is discussed. For evaluating self-cleansing conditions, the critical velocity and the critical shear stress were computed according to the Shield's equation. In the SDGS, both critical velocity and critical shear stress assume values significantly lower than in conventional gravity sewers, for ensuring the same self-cleansing conditions, due to the particular effluent characteristics. In this situation, and according to the computations, a critical velocity of 0.15 m/s or a critical shear stress of 0.15 N/m$^2$ seem to be high enough to ensure scouring conditions. In those circumstances, the risks of sedimentation and blockage in SDGS do not seem to be significant.

On the other hand, the risks of sulphide generation along unconventional small gravity sewer systems flowing in surcharged conditions seem to be high, when compared with the risks of sulphide generation and occurrence of septicity in conventional small gravity sewers. The risks may be possibly significantly reduced if these systems do not include long reaches flowing in surcharged conditions or if correction measures to control septicity are implemented.

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