Teka Kom. Ochr. Kszt. Środ. Przyr. – OL PAN, 2010, 7, 272–279

ECONOMIC ANALYSIS OF SMALL DIAMETER GRAVITY SEWERS COMPARED TO OTHER SEWERAGE SYSTEMS

Tadeusz Nawrot

Department of Hydraulic and Sanitary Engineering, Poznań University of Life Sciences
Piątkowska str. 94A, 60-649 Poznań, tnawrot@up.poznan.pl

Summary. The paper presents a general idea of small diameter gravity sewers. An economic analysis of small diameter gravity sewers with pretreatment of domestic wastewater in septic tanks is presented. The system has proved to be the cheapest compared with conventional gravity as well as pressure sewerage.

Key words: small diameter gravity sewers, septic tank, economic analysis, capital cost per one household

INTRODUCTION

The small diameter gravity sewage system is an alternative to conventional gravity sewers. It is used in sparsely inhabited settlements, undulating or flat terrain (small slopes) and high groundwater levels. It is a system in which the wastewater flows from household to septic tanks (ST) in which it is pretreated. Mainly, this will reduce the concentration of the suspended solids. At the outlet of each ST an outlet filter is mounted to enhance suspended solids removal in ST. In addition, in some cases check valves are used to prevent backflow of wastewater to ST and inflow of air to the network. Wastewater from ST is further transported by pipes with small diameters (32–100 mm), made of plastic (PE or PVC), to a wastewater treatment plant (WWTP). The pipes of small diameter gravity sewage systems (SDGSS) can be laid parallel to the ground surface even with a negative slope. This system can also work with domestic pumping stations used to transport wastewater from low-lying points in relation to the sewer collector.

This system was created in the sixties of the 20th century in Australia [Otis *et al*. 1985]. Low investment costs resulted in rapid development of the system, especially in southern Australia. In 2001, such systems in Australia served over 110 000 inhabitants [Palmer *et al*. 2010]. In Poland, this system is being implemented with positive effects for several years by the company Biotop from Zamość and the Section of Rural Water Supply & Sanitation, Poznań University of Life Sciences. The first system in Poland was created in 1995 in the village Nieledew [Błażejewski and Skubisz 2005]. It supports about 400 inhabitants and, so far, works reliably. Underdevelopment of this system in Poland is mainly due to lack of expertise and the belief in the superiority of the conventional gravity sewers by designers, although the latter may be even twice as expensive [Błażejewski and Skubisz 2005] in the case of sparse development, high groundwater level, flat or undulating terrain.

An additional problem is the design of this type of sewer, and it is related to the lack of good knowledge on the hydraulic conditions of the network. For example, different authors give different rates of self-cleaning velocity of the pipe: 0.5 $m \cdot s^{-1}$ – Otis and Mara [1985], 0.3–0.45 $m \cdot s^{-1}$ – Bowne *et al*. [1991], 0.15 $m \cdot s^{-1}$ – Dias and Matos [2001], 0 for low concentration of the suspended solids – Little [2004], 0,2 $m \cdot s^{-1}$ – Kreissl *et al*. [2008].

One of design mistakes is accepting the average velocity for the maximum hourly flow Q_{hmax} as computational velocity for the network. More realistic are instantaneous (averaged over minutes) maximum velocities, much higher than the average hourly velocity. Therefore it was necessary to create a mathematical model describing the hydraulic conditions in the network during the flow of wastewater (a quasi-steady flow) and used to optimise the selection of pipe diameters and the size of septic tanks [Nawrot 2010].

MATERIALS AND METHODS

Choosing the best sewage system for the field conditions requires a comparison of the effects of economic, environmental and social impact caused by the investment. In order to evaluate and compare various types of systems one should determine their investment and operating costs, and then calculate the economic efficiency of the investment. To evaluate the effectiveness of the investment an expected annual cost, expressed by the following equation, was applied:

$$K_r = \frac{p(1+p)^n}{(1+p)^{n-1}} \cdot I + K \quad \text{zł a}^{-1} \tag{1}$$

where:
I – capital cost of investment, PLN,
p – discount rate,
n – life cycle duration in years, a,
K – annual operation and maintenance costs, PLN a^{-1}.

The discount rate to compare economic effects was assumed to be equal to p = 0,05 and the life cycle of the investment equal to n = 50 years. A comparison of conventional sewage systems and pressure systems with the SDGSS was made. The capital costs per one dwelling unit (household) and unit cost indicators per one equivalent dwelling units (EDU) and wastewater price was specified, as follows:

$$W = \frac{I}{EDUs} \quad \text{PLN EDU}^{-1} \tag{2}$$

$$W_G = \frac{K_r}{EDUs} \quad \text{PLN EDU}^{-1}\ \text{a}^{-1} \tag{3}$$

$$W_S = \frac{K_r}{365 \cdot Q_{dsr}} \quad \text{PLN m}^{-3} \tag{4}$$

where:
I – capital cost of investment, PLN,
$EDUs$ – number of equivalent dwelling units, EDU,
K_r – the expected annual costs, PLN a^{-1},
$Q_{dśr}$ – average daily flow of wastewater, m^3 d^{-1}.

Capital and operating costs of different sewerage systems for 250 households inhabited by four people each were estimated. Volume of wastewater per capita was taken as 120 $dm^3 \cdot d^{-1}$. The length of connections for each household was assumed to be equal to 15 m, the average distance between households 10, 40 and 90 m, and the groundwater level of 1.5, 3 and 5 m below ground level, slopes in the direction of WWTP to equal 0 (flat terrain), 3 and 5 ‰ were assumed.

For SDGSS investment in the network, ST and WWTP and operational costs of the network, ST and WWTP were distinguished. Capital cost for the network was based on the assumed cost per unit length equal to one meter of the network, 136 PLN$\cdot m^{-1}$, and the total length of the networks and connections. Laying pipes parallel to the ground at a depth of 1.5 m allowed for neglecting the cost of trench dewatering. Such a low unit cost of the network was possible due to the application of trench-less or narrow space excavation. In addition, the cost of a pumping station at the WWTP in the amount of 50 000 PLN was added. Capital cost for the WWTP was estimated based on investment cost per unit capacity [Matz 2006] equal to 12 000 PLN m^{-3} d but, due to the fact of pretreatment of wastewater in the septic tank, this value was reduced by one third. Thanks to the STs, investments on the mechanical part of the WWTP were excluded. For other systems, these costs were assumed equal to 12 000 PLN m^{-3} d. Capital cost for the STs was estimated assuming the cost of one ST with fittings and assembly equal to 4500 PLN. Operation of SDGSS is limited to its cleansing to prevent the deposition of suspended solids and biological membrane fouling of the pipes. The operation costs of STs was valued at 0,4 PLN $EDU^{-1}a^{-1}$, assuming one cleansing every 6 years. WWTP operating costs were determined on the basis of the expected annual cost of WWTP [Miłaszewski 2003]:

$$K_{r\,OS} = 0{,}4 \cdot Q_{OS}^{0{,}75} \cdot \left(\frac{\eta}{1-\eta} \right)^{0{,}486} \tag{5}$$

where:
$K_{r\,OŚ}$ – annual O&M cost of WWTP, mln PLN $a^{-1,}$
$Q_{OŚ}$ – WWTP capacity, mln m^3a^{-1},
η – effectiveness of organic substances (as BOD_5) removal.

This equation is valid for a WWTP with a capacity from 100 to 20 000 $m^3 \cdot d^{-1}$, assuming the interest rate of 5%, and twenty years of life. These costs depend on the assumed efficiency of the WWTP. BOD_5 ratio was adopted after the STs equal to 100 $g \cdot m^{-3}$. For the required value of BOD_5 in the final effluent of 40 $g \cdot m^{-3}$ the required value of efficiency was 0,6. For other systems, the concentration of organic matter in the inflow to WWTP was adopted as 300 $g \cdot m^{-3}$, and $\eta = 0.86$. Exploitation of ST is associated with the emptying of the sludge in an amount of 1.5 m^3, every three years. The expense of emptying consists of the cost of sludge transporting to the WWTP (20 PLN $EDU^{-1}m^{-3}a^{-1}$) and the cost of sludge treatment (10 PLN EDU^{-1} $m^{-3}a^{-1}$).

Capital and O&M costs of pressure sewerage system consist of the same elements as SDGSS with the STs replacement by household sewage pumping stations. Expenditures on the network by adopting the same price per unit length were similar to those for the network of SDGSS, as the investment cost of sewage pumping station was comparable to that of cleansing station (100 000 PLN). Expenditures for pumping stations were calculated on the basis of unit price equal to 7260 PLN per assembly. Operation and maintenance of the pumping station involves servicing the pumps (20 PLN $EDU^{-1}a^{-1}$) and electrical energy costs, assuming a price equal to 0.44 PLN/kWh, pump power of 1.8 kW and 8 minutes work during the day. Operating costs include network cleansing three times per day with compressed air supplied from a compressor of power of 11 kW working 15 min/d.

A gravity sewerage system consisting of a network and WWTP was analysed. Capital costs of the network depend on the local slope of terrain. Minimum slope of pipe equal to 5‰ was adopted. If the slope of terrain was equal to 5‰, the network was designed in parallel to the ground surface. Minimum soil cover of pipes was 1.4 m and the maximum – 5.0 m. When the depth exceeded 5.0 m a pumping station was taken into account. The costs of laying pipes along the manholes were adopted depending on the depth of installation of pipelines. The unit cost of the gravity networks ranged from 250 PLN for a backfill height of 1.4÷1.85 m to 500 PLN for height of 4.55÷5.0 m. In addition, these expenditures include the costs of trench dewatering depending on the level of groundwater. Unit cost reduction of groundwater level by one meter per one meter of the network was assumed to be equal to 200 $PLN \cdot m^{-1}m^{-1}$, excluding connections because their depth was taken as 1.2 m. The length of the main collector was assumed to be equal to one-third of the total network length. For this length the number of pumping stations was determined by dividing the length of the collector by the length with the constant slope of ground, at which the backfill height of pipes was 5 m. The price of one pumping station was set at 100 000 PLN. Before the WWTP another pumping station was included in the design. O&M of gravity sewage system depend on it cleansing at specified periods of time and delivering power for the pumping. Cost of the network flushing was assumed to be equal to 6 $PLN \cdot m^{-1} \cdot a^{-1}$ [Ćwiertnia 2004] for flushing frequency every 5 years. The cost of pumping energy was calculated assuming for the pump set of power 3 kW, working for 3 hours a day.

RESULTS

Figure 1 shows the impact of the average interval between households, slopes of terrain and the groundwater level on the capital cost per one household of the sewerage network and WWTP costs for the assumed network consisting of 250 households located along one street side. When buildings are located on both street sides, investment would be 50% lower. Effect of average interval between households, slopes of terrain and the groundwater level on the unit wastewater price is shown in Figure 2.

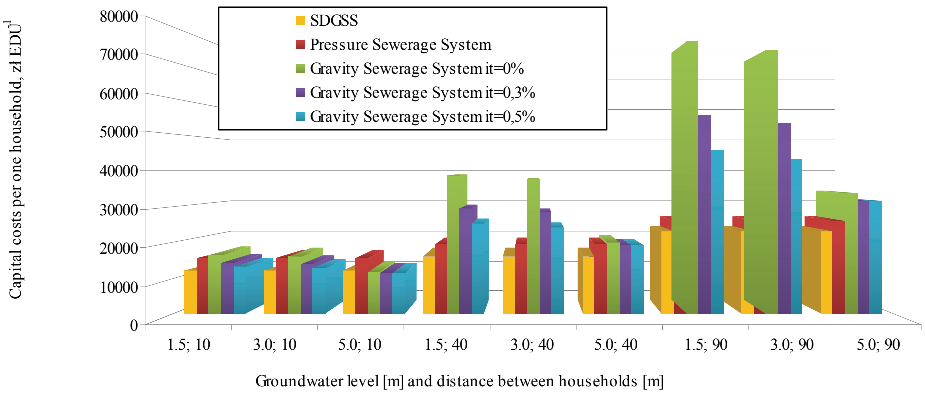

Fig. 1. Effect of average distance between households, slope of terrain (it) and groundwater level on the capital costs per one household, PLN EDU^{-1}

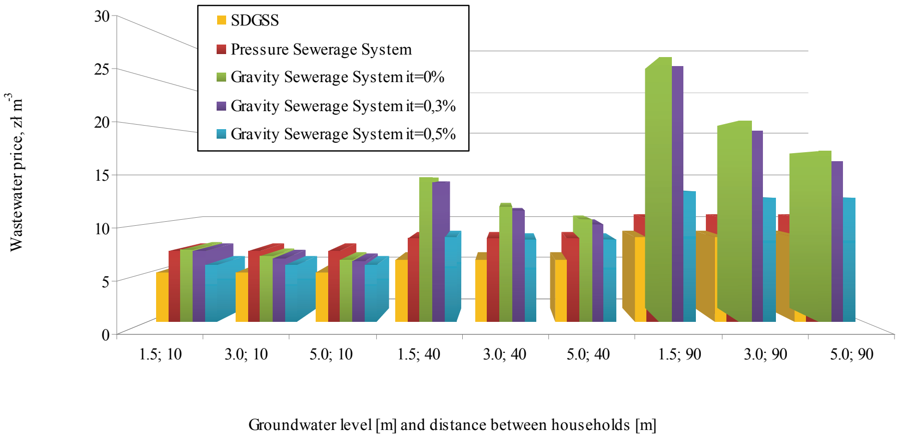

Fig. 2. Effect of average distance between households, slope of terrain (it) and groundwater level on wastewater price, PLN·m^{-3}

DISCUSSION

The expected average annual costs of the sewerage network and WWTP costs for SDGSS turned out to be the lowest compared to other systems for given field conditions. However, for distances between households equal to 10 m, these costs were almost comparable to the cost of gravity sewers assuming a level of groundwater 5 m under terrain surface. The most expensive at this distance it appears to be the pressure system, but its costs do not differ from those of conventional sewage systems with a high level of groundwater and small slopes in the direction of WWTP. As the distance between households rises, the cost of gravity sewers (especially at high groundwater level) is higher and the difference between SDGSS and pressure systems decreases. The capital cost per one household is also the lowest for SDGSS. There is also a pronounced difference between the capital cost of gravity sewerage and SDGSS. The highest capital cost at a low distance between households is generated in the case of the pressure system, and at a long distance – gravity sewage systems (the most at a high groundwater level).

Unit total cost per household for SDGSS ranged from 890 to 1561 PLN EDU^{-1}a^{-1} in contrast to gravity sewers, where the unit cost per household in the cheapest case was 1031, and in the most expensive 4735 PLN EDU^{-1}a^{-1}. In the worst case scenario, this cost was three times higher. In the case of the pressure sewerage the unit cost ranged from 1277 to 1926 PLN EDU^{-1}a^{-1} and was approximately 20% higher than the cost of SDGSS. The estimated unit price of wastewater shows a similar trend. The price of 1 m^3 of wastewater ranged from 5.1 to 8.7 PLN m^{-3} in contrast to the gravity sewers where the price was in the range of 5.8 PLN m^{-3} up to 27 PLN m^{-3}.

CONCLUSION

On the basis of estimates of capital cost and operating costs of systems it can be stated that the SDGSS at low density and high groundwater level is three times cheaper than a conventional gravity system. Only at small distances between the households and low groundwater levels the gravity sewers would be cheaper than SDGSS. The most competitive system with large distances between households appears to be the pressure system, but it turned out to be about 20% more expensive. A large part of the Polish rural areas is characterised by high levels of groundwater and sparse development, therefore the SDGSS should have a good chance for future growth. Revenues of Polish rural communities are not high, thus it is very important to choose cheap systems with the highest economic efficiency, especially in the future when financing of these projects will disappear from UE funds after 2015. The decision to build a sewerage system should be preceded by carrying out an analysis of the expected annual costs for several variants of sewage systems, not just for a few variants of gravity sewers.

REFERENCES

Błażejewski R., Skubisz W., 2005. Small diameter gravity sewers – a new proposal for Polish rural areas. Scientific Papers of the Kielce University of Technology, Budownictwo 44.

Bowne W.C., Naret R.C., Otis R.J., 1991. Alternative wastewater collection systems. EPA-625/1-91-024; US EPA, Office of Water, Washington, D.C.

Ćwiertnia R., 2004. Exploitation of objects and sewerage networks and their monitoring, in: Ogólnopolska konferencja szkoleniowo-techniczna „Ścieki – eksploatacja oczyszczalni i instalacji ściekowych". Poznań – Tarnowo Podgórne.

Dias S.P., Matos J.S., 2001. Small diameter gravity sewers: self-cleansing conditions and aspects of wastewater quality. Water Sci. Technol., 43, 5, 111–118,

Kreissl J., Linahan D.V., Naret R., Lombardo P., 2008. Alternative Sewer Systems – MOP FD-12, 2nd Edition. WEF Press, Alexandria, Virginia.

Little C.J. 2004. A comparison of sewer reticulation system design standards gravity, vacuum, and small bore sewers. Water SA, 30, 5, 685–692.

Matz R., 2006. Rules for exploitation of individual and collective sewage treatment plants. Gaz, Woda i Technika Sanitarna, 5, 28–31.

Miłaszewski R., 2003. The economics of surface water protection. Wyd. Ekonomia i Środowisko. Białystok.

Nawrot T., 2010. Mathematical model of small diameter gravity sewers with check valves, in: Materiały z 3rd International Interdisciplinary Technical Conference of Young Scientists, 19–21 May 2010, Poznań, Poland.

Otis R.J., Mara D., 1985. The Design of Small Bore Sewer Systems. United Nations Development Programme, Interregional Project INT/81/047 http://www.wds.worldbank.org/servlet/-WDSContentServer/WDSP/IB/2000/01/06/000178830_98101903445889/Rendered/PDF-/multi0page.pdf

Palmer N., Lightbody P., Fallowfield H., Harvey B., 2010. Australia's most successful alternative to sewerage: SA's septic tank effluent disposal schemes. http://www.efm.leeds.ac.uk/CIVE/-Sewerage/articles/australia.pdf

ANALIZA EKONOMICZNA KANALIZACJI MAŁOŚREDNICOWEJ W PORÓWNANIU Z INNYMI SYSTEMAMI KANALIZACYJNYMI

Streszczenie. Artykuł przedstawia ogólną ideę grawitacyjnej kanalizacji małośrednicowej. Przeprowadzono analizę ekonomiczną kanalizacji małośrednicowej, w której ścieki są wstępnie oczyszczane w osadniku gnilnym. System ten okazał się najtańszy w porównaniu z tradycyjną kanalizacją grawitacyjną, jak i z kanalizacją ciśnieniową.

Słowa kluczowe: kanalizacja małośrednicowa, osadnik gnilny, model matematyczny, obliczenia hydrauliczne