Practical Paper

An economical, environmental, and social comparison between vacuum and gravity sewers in decentralized sanitation systems, with Egypt as a case study

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ABSTRACT

The conventional gravity sewer is the most commonly used rural sewerage system in developing countries. However, this system has many technical, economic, environmental, and social disadvantages. Vacuum sewers could serve as a good competitor as an alternative system to conventional gravity sewers. A sample of 33 rural villages with populations of <10,000 people is selected from Egypt. A statistical analysis was done using SPSS and STATISTICA software where population and area variables had the most significant effect on the calculation of investment, operation, and maintenance costs. It was found that investment costs for the vacuum system were mostly lower than for the conventional one, while operational and maintenance costs played significant roles. Prediction models were obtained based on multiple quadratic regression models. It was found that the vacuum system was economically competitive in large villages with low population densities. Environmentally and socially, the vacuum sewers proved to be better than gravity sewers.

Key words | decentralized systems, gravity sewers, vacuum sewers

INTRODUCTION

This study focuses on sewerage systems for rural decentralized areas in developing countries, with Egypt as a case study, where rural sanitation coverage is still incredibly low (Abdel-Gawad 2007). The implementation of sewerage systems in the agricultural villages and rural areas of Egypt has faced many challenges, which mainly are: shallow groundwater, flat landscapes, narrow streets, tunnels required to cross under existing waterways, deep excavations, as well as the need for intermediate lift stations.

Most of the projects carried out in developing countries are using the traditional conventional gravity sewers. Even when conventional sewers are more expensive than alternative sewers, their use may still be preferred given that they are an old and mature practice (EPA 1991). Conventional gravity sewers are an economic system for settlements with high densities. In regions with flat or undulating topography, sections of the gravity sewer line may need to be buried deep. Lift stations are required at low points or where other existing infrastructure and natural obstacles must be avoided (ROEVAC 2012). The application of this system in rural areas with flat terrain is costly and may not be the ideal solution.

International experience has shown the value of various alternative wastewater collection systems that can be implemented in developing countries (Ashipala & Armitage 2011). Consequently, searching for sanitation systems that can offer economic, environmental, and social sustainability becomes the major concern, especially when the budget for sanitation projects runs into billions of dollars throughout the world. Recently, vacuum sewers have been used extensively and proven to be both practical and cost-effective (ROEVAC 2012).

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Vacuum sewer systems are installed in numerous countries around the world. These systems have three main components: valve chambers, vacuum sewers, and the vacuum station (RediVac 2004). Vacuum sewage collection systems operate in such a way that wastewater from each property flows by gravity into the wet sump of the valve chamber. The vacuum valve in the chamber automatically opens and the liquid, followed by a quantity of air, is rapidly drawn into the vacuum sewer. Vacuum sewers are usually a jointed polyethylene electro-fusion pipe laid at shallow depths in a saw tooth profile, with a diameter range between 90 and 250 mm (ROEVAC 2012).

Some recent research has studied the vacuum system in comparison with conventional and other sewerage systems (Haarhoff 2008; Ashipala & Armitage 2011; Hensely 2012; Panfil et al. 2015) with a focus mainly on the investment cost and the potential impact to the environment. These studies agreed that the vacuum sewerage system is an advantageous method for collecting wastewater, in terms of technical, economic, and social requirements compared with the conventional system. However, the comparison between vacuum sewer systems and conventional systems in terms of operation and maintenance (O&M) costs has not been studied in any research. The implementation of vacuum sewerage systems in rural settlements in developing countries, based on real case studies, has not yet been done.

This paper presents a comprehensive comparison between conventional gravity sewers and vacuum sewers with recommendations on implementation of vacuum sewers in developing countries. O&M approaches and costs are discussed and compared, and the environmental and social impacts of each system are assessed.

**MATERIALS AND METHODS**

In order to have a reliable economic comparison between gravity and vacuum sewerage systems, 35 rural agricultural villages were chosen from Egypt. The sample size was determined using Equation (1) (Naing et al. 2006):

\[ n = \frac{Z^2 P(1-P)}{d^2} \]  

where \( n \) is the sample size, \( Z \) is the statistic for a certain level of confidence, \( P \) is the expected prevalence or proportion, and \( d \) is the precision. The \( Z \) statistic for the level of confidence of 95% typically equals 1.96. Taking into consideration Equation (1) and the prevalence of small and medium villages as 80% of Egyptian villages (World Bank 2005) and within this population range, the precision in this case will range between 10 and 15%.

Different populations and areas were considered during sample selection. The selected sample was with a population ranging from 100 to 10,000 people covering areas from 0.90 to 90 hectares and population densities from 64 to 495 persons per hectare. Selected sample areas were with similar characteristics, such as a flat to semi-flat ground slope, high groundwater table, narrow streets, and several waterways.

For all chosen villages, detailed hydraulic designs were conducted for both conventional and vacuum systems for, typically, an economic life of about 35 years (ECP 2010). For a conventional system, the investment cost was calculated for gravity sewers, manholes, and pumping stations. For a vacuum system, the investment cost was calculated for vacuum sewers, collection chambers, including the vacuum valves, vacuum station, and the cost required for social awareness as additional services were required for success in rural areas, especially in developing countries. The cost of mutual components, such as the house connection pipes and inspection chambers is not considered. O&M costs are calculated for energy consumption, labor requirements, spare parts, renewal, replacement of equipment within 35 years (such as renewal and replacement of pumps, vacuum pumps, vacuum valves, and controllers), regular maintenance required for sewers and stations, diesel required for generators, the renting of machines, and any other additional costs.

Annual investment cost was calculated for all 33 villages by dividing the total investment cost by the economic life. The total annual cost includes the combination of the annual investment cost and annual O&M costs. This practice is commonly used in Egypt during feasibility studies neglecting inflation rates.

The variables: population, area, terrain slopes, investment cost, as well as O&M cost were inserted into the statistical analysis software SPSS version 18 for statistical analysis and STATISTICA version 10. Correlation between the different variables was obtained in order to determine
the most effective variables on the selection between both systems. The statistical predicting model is derived using multiple regression analysis and is employed to obtain information as to when and where any system could be used.

RESULTS AND DISCUSSION

Economic aspects

The variable ‘ground slope’ was found to be insignificant with annual investment, O&M, and total annual costs (p values = 0.38, 0.48, and 0.42 > 0.05, respectively) as it only had a minor effect on the cost of the two sewer systems. This was due to the fact that the slopes ranged from almost flat to 0.95% which is considered as flat (slopes <2% are flat, McDonald et al. 1990). This also explains the high cost of gravity sewers in this case. The population density correlation (R) to the different costs was found to be both small and insignificant (p values = 0.13, 0.06, 0.10 > 0.05, respectively).

Population and area had the best correlation and were considered to be the variables with the most influence on the costs (investment, O&M, and total cost). Multiple quadratic regressions gave the best fitting (R²) within the sample boundaries (selected population and area range). The prediction quadratic models are shown in Figure 1. In general, the x-axis, y-axis, and z-axis represent the areas (hectares), the population (persons), and the costs (EGP × 10⁴ ~ K€), respectively.

It was discovered that the agricultural villages contain many drains and canals, and, consequently, crossings under these waterways will be required. Thus, the investment cost of the gravity networks increases significantly. In vacuum sewers, simple and cheap crossings are used, and, consequently, the networks are considered as the cost saving factor.

The cost of the vacuum collection chambers is mainly dependent on the number of households. Therefore, as the population increases, the required number of collection chambers will also be higher. The cost of the pumping stations is mostly higher than the vacuum station, which is considered as a unique feature for villages with high groundwater tables, since the cost of plunging the pump sump significantly affects the total cost of the pump station.

Investment costs are always higher in gravity sewerage systems, as shown in Figure 1(a) and the O&M cost plays an important role in identifying the suitability of the two systems. On average, the O&M cost for vacuum sewers is higher than the O&M cost for a conventional system by 1.30 (Figure 1(b)). Regarding the total annual cost, Figure 1(c) shows that the cost saving advantage of the vacuum sewerage system does not always exist. The vacuum system could be a good competitor, but only in certain conditions.

The vacuum system is more economically suitable for big areas with low population densities (<200 persons/hectare) and population size of >3,500 up to 10,000. In general, it was realized that the total cost for gravity sewers is cheaper in small areas (i.e., <30 hectares). For example, a big village with 8,000 persons and 60 hectares was found to have a 10–15% saving when using a vacuum system. This followed from the advantage of using simplified pump stations in addition to the existence of shallow sewers caused by reductions in the lengths of the sewers. In addition, the number of manholes is fewer. In this case, the cost of vacuum stations becomes the reason for the increase in cost. This conclusion is, however, limited to the sample used in this study.

Recommendations for successful use of the vacuum sewerage system in developing countries may be as follows:

- The construction materials, including the pipes and inspection chambers, should be manufactured locally.
- Design and construction should be under the supervision of international consultants or organizations experienced in this field.
- Regular inspection of system components by staff or remote monitoring has to take place.
- Social awareness and training should be provided to the villagers to explain the importance of vacuum systems, as well as general guidelines on how to use them.

Although the aforementioned recommendations are proposed, from a technical point of view, O&M of the system in remote areas may be a problem. From the available literature, it appears that the system can easily be kept successfully operational in developed countries. However, no literature was found on the application of vacuum sewers in rural communities in developing countries. Hence, the outsourcing of O&M may be a viable alternative; otherwise, social mobilization, training, and regular visits from the responsible authorities should take place to help the households to manage the system by themselves.
Figure 1 | Quadratic regression model for (a) investment cost, (b) O&M cost, and (c) total annual cost.
Environmental aspects

The most used materials in the construction of the sewerage projects are the pipelines and materials required for manholes, collection chambers, and bedding. In Egypt, and for this range of population, PVC (polyvinyl chloride) pipes are always used. The information regarding the length of pipelines and the specific weight per 1 meter for PVC pipes with classification SN 8 for conventional sewers and classification PN 10 for vacuum sewers are available in the local market. In this study, it was found that the specific weight needed for constructing the conventional sewers is 13 kg PVC/person compared with only 8 kg PVC/person needed for vacuum systems. With regard to the construction materials required for the bedding and backfilling of the pipeline trench, it was found that the average trench volume required for the conventional sewers is 2.25 m³/m compared with only 0.90 m³/m required for vacuum sewers. In addition, the number of manholes required is 8,765 compared with only 4,201 collection chamber required for the vacuum system. As a consequence, the potential of resources’ depletion and the consumption of energetic resources is higher in the conventional system. The construction of the conventional system requires heavy equipment and a long construction time, which results in degradation of air quality due to dust rising during construction, and also produces noise pollution.

Vacuum sewers are sealed and continually under vacuum which prevents the in/exfiltration to/from the sewers and keeps the groundwater free from contamination especially when it is used as a source for irrigation and drinking purposes. This advantage probably does not materialize in the conventional system. The velocity of the water inside the vacuum sewers reaches 6 m/s making obsolete the potential of clogging, while in the conventional sewers, this problem commonly exists with fewer ways of discarding the clogging materials. The wastewater in the conventional sewers is commonly exists with fewer ways of discarding the clogging materials. The wastewater needs to be treated using biological or chemical methods, while in the conventional sewers, the wastewater is discharged into water bodies or treated using biological or chemical methods. The energy consumption of the vacuum stations was found within the sample to be lower than the pumping stations with about 30–50% depending on the size of the village.

These findings are consistent with previous research that studied the environmental impact for the vacuum system with different assessment tools, such as the global pollution index methodology (Panfil et al. 2015) and the triple bottom line methodology (Haarhoff 2008). Our study concluded that the vacuum system has less negative impacts on the environment than the conventional system and is expected to have the best environmental sustainability.

Social aspects

The alternative sewerage schemes that have been undertaken in other developing countries’ urban informal settlements have revealed that it is social and institutional factors rather than technical, environmental, or even financial considerations that pose the greatest impediment to the implementation of alternative sewerage (Silveira 2002; Parkinson et al. 2007). In general, the construction and operation of sanitation projects have major positive social impacts which can be: (1) provision of job opportunities, (2) improvement in quality of life, and (3) increase in standard of living.

On the other hand, one of the negative social impacts of conventional sewers is the deep and wide trenches created during construction which cause many losses and cracks in existing buildings. In addition, the roads are blocked due to the movement of the heavy equipment. These requirements increase the potential for accidents and injuries during construction and extend the construction time. Construction of vacuum sewers can overcome and decrease the potential of the aforementioned shortcomings. During the O&M phase and for the same capacities of sewers and stations, the employment opportunities for the vacuum system increase compared with the conventional system. It may be costly to have a higher number of operators but it is still useful to the community.

In general, the success of sanitation in the rural areas is the result of an effective partnership between the sewerage authority and the community. Often, it is underestimated what it takes to bring about changes in behavior, including community members’ changing from passive to active roles. Institutionalizing community participation in all types of sanitary service provision and mobilizing non-governmental efforts and resources into community awareness is highly recommended.
It has to be noted that the incorporation of community involvement in sanitation service provision projects is by no means an easy task (Ashipala & Armitage 2011). To keep the sustainability of a vacuum sanitation project, the following chain is proposed:

1. Awareness and training
2. Regular and proper O&M from the community
3. Cost recovery from the community
4. Permanent support from the sewerage authority.

From the community perspective, the vacuum system will offer stability during the construction; however, the community should be aware that their responsibilities regarding sustainability is increased compared with the conventional system.

CONCLUSIONS

A comprehensive comparison between conventional gravity and vacuum sewers in 33 villages in Egypt, undertaken in this study, showed that the investment cost of the vacuum system is, in most cases, lower than that of the conventional system. In general, vacuum sewers were found to be economically advantageous in large villages from 30 to 90 hectares with population densities <200 persons/hectare. However, availability of the construction material and equipment in the local market, which is mostly available in the Egyptian market, greatly influences the investment cost of the vacuum system. Vacuum sewers showed less negative environmental and social impacts than the conventional system. Capacity building and social mobilization can also play a significant role in the sustainability of this system. However, the challenge here may be how to help the communities in the management, operation, and maintenance of the vacuum system. Awareness-building of the villagers should take place before starting the implementation in order to check their capability and responsibility.

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