Proceedings of the 4th International Conference on Environmental Pollution and Remediation
Prague, Czech Republic, August 11-13, 2014
Paper No. 82

Vacuum Sewerage System in Developing Regions and the Impact on Environmental Management

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Abstract – Leakage in sewerage system can cause groundwater and soil contamination in urban areas, especially in area with a high groundwater table. This is a serious problem in small agricultural villages which rely on ground water as a source for irrigation and drinking purposes. In the developed countries, the recent trend in areas with low population densities is using vacuum sewerage system. Vacuum system could be environmentally safer than conventional gravity system, protecting public health, preventing exfiltration to the ground water, very easily applied in a relatively short time, and can cope with a faster expansion of the urbanized areas. Detailed hydraulic design were held for both gravity sewer and vacuum sewer systems in 28 Egyptian agricultural villages as a case study for developing regions. Different conditions, such as population, areas, and terrain slopes were evaluated. Cost comparisons based on statistical analysis were done to assess the feasibility of using vacuum sewerage in developing regions. Based on this study, from financial point of view, vacuum sewerage system was a good competitor to conventional systems in flat areas and areas with high groundwater table. From the environmental point of view, it is recommended to construct the vacuum sewerage system in such agricultural villages. The local market supplying of the construction equipment especially collection chambers will greatly affect the investment cost. Capacity building and social mobilization will also play a great role in sustainability of this system.

***Keywords*:** Conventional sewer system, Vacuum sewer system, Developing regions, Statistical analysis.

1. Introduction

Wastewater is originating from domestic, commercial, and industrial sources (often mixed with storm water) are collected, treated, and discharged back into the environment. Protecting wastewater collection and treatment systems with the least risk to public health and safety in the most cost effective manner is the goal of any sewer construction system (Stanko and Mahríková, 2009). Leakage from conventional sewerage systems can cause groundwater and soil contamination, especially in area with a high groundwater table. Damaged sewers can cause groundwater and soil contamination with sulphate, chloride, and nitrogen compounds. This is a serious problem in small villages in developing countries, where it usually rely on ground water as a source for irrigation and drinking purposes.

Egypt as a case study for developing countries is facing difficulties to connect all households in rural areas to wastewater services. Rural sanitation coverage in Egypt remains incredibly low at 11%. The low coverage, in combination with a sub-optimal treatment, results in serious problems of water pollution and degradation of health conditions because the majority of villages and rural areas discharge their raw domestic wastewater directly into the waterways. The discharges are increasing year after year due to the population growth as well as the rapid implementation of water supply networks in many villages without the parallel construction of sewage systems. Delays in achieving sufficient sanitation services are due to financial constraints. This pollution causes 17,000 children deaths yearly in Egypt (Abdel Gawad, 2007). Proceeding from this, searching for low cost technologies becomes the major concern with keeping the environmental sustainability and public health.

Conventional gravity sewers is considered the only system used in Egypt and many other developing countries. Conventional gravity system is an economic system for settlements with high densities (Roevac, 2012). The conventional gravity sewer system is working on the principle that water flows downhill. Manholes are used as interceptor, and inspection for the gravity pipes. Because of this basic principle, this type of collection system has been used for thousands of years and has been widely accepted as the standard by which all other collection systems are compared; thus, all other forms of collection systems have been deemed “alternative” (William, 2012).

Conventional gravity collection systems must be designed to maintain minimum slopes to ensure that minimum flow velocities (typically 0.6 m/s are achieved when flowing full). In regions with flat or undulating topography, sections of the gravity sewer line may need to be buried deep in order to maintain minimum slope requirements. Lift stations are required at low points where minimum slopes can no longer be maintained or where existing infrastructure must be avoided (William, 2012).

Because conventional gravity sewers are prone to infiltration and inflow, due to leaking joints, leaking service laterals and leaking manholes, treatment plants should be sufficiently sized to accommodate infiltration due to high ground water or storm events in some regions. This not only adds to the cost of the collection system but also increases the cost of the treatment plant as well; however, failure to size the treatment facility to accommodate these surge events will result in the discharge of partially or totally untreated wastewater into the environment (William, 2012).

Conventional gravity collection systems are not typically the most effective collection and transference method in a variety of applications. For example, in rural communities (especially those with low population density), rocky terrain, flat or undulating terrain, as well as existing communities, alternate forms of wastewater collection are generally a more viable alternative to conventional gravity sewers because of their lower installation costs. In existing communities, constructing conventional gravity collection systems can create extended disruption due to their relatively slow installation time, as well as the necessity of utilizing heavy equipment, and deep wide trenches.

Conventional sewerage system could have a negative impact on underground water because of leaky sewers. A better solution is to use sewer pipes with built-in seals such as vacuum sewerage systems (Stanko and Mahríková, 2009). Vacuum sewers are continually under vacuum, minimizing the potential for leaks. Vacuum sewerage systems are used nowadays in decentralized areas in Europe and USA. This system could ensure environmental sustainability and protect public health.

The first vacuum sewerage system was built in the Netherlands for the first time in the 1860’s (RediVac, 2004). Vacuum Systems have been installed in numerous countries around the world. Vacuum systems have three main components, valve chambers, vacuum sewers and the vacuum station (RediVac, 200). A typical vacuum system for sewage collection essentially comprises of (1) Gravity Collection System (service lines) - a gravity sewer serving each property designed and operated as a conventional gravity sewer, (2) Collection Chambers - chambers into which the gravity sewer lateral pipes connect. Each chamber houses a vacuum interface valve and typically serves between 4 and 6 properties. Chambers are similar to conventional sewer manholes and are generally about 2m deep, (3) Vacuum Sewer - operates under a vacuum pressure of about -0.7 bar and connects the interface chamber to the vacuum station. The vacuum sewer is usually polyethylene electro-fusion jointed pipe laid at a depth of about 1.5m in a saw tooth profile, (4) Vacuum Station - comprising a sewage collection vessel, vacuum pumps, sewage discharge pumps and associated control gear.

Vacuum Sewer pipes with diameter range between 90 to 250 mm are usually laid at average depths of only 1.0 to 1.2 m with minimum slope of 0.2 % (Roevac, 2012). Vacuum sewer systems allow using comparable low design flows per capita as any filtration water can be terminated. The total hydrostatic lift height within a vacuum line should not exceed approximately 4 m resulting to about 4 km longest vacuum lines in flat areas or a maximum catchment diameter of 8 km around the central vacuum station. The remaining vacuum pressure of 3 m is required for the operation of the vacuum valves (Roevac, 2012). Vacuum vessel could be concrete dome or steel. Special attention is required during the design of the sewage pumps due to the law availability of net positive suction head (NPSH) to avoid the cavitation.

The vacuum companies claim that vacuum sewer collection systems have proven to be a practical when the local topography is flat and thaw unstable ground prohibits buried utilities. They claim that vacuum sewers were feasible and more cheaper than conventional sewers in many situations. These situations are given below:

- Where the slope of the ground is relatively flat. A gravity sewer becomes deep in these cases in order to adhere to minimum velocities and it becomes necessary to install pumping stations. In certain circumstances, the number of pumping stations can be excessive and they require specialised maintenance.
- If there is rock close to the ground surface, running sand or a high water table it is expensive and difficult to dig deep trenches.
- In situations where potable water is in short supply and/or the people are poor, it has often been found that flushing velocities in gravity sewers are difficult to attain and maintain. A vacuum system relies on the negative pressure to propel the liquid at scouring velocities and it is largely independent of the volumes of water used.
- Where the population density (people per hectare) is low (Ninham, 2004).

The situations described above invariably result in a lower capital cost for installation (have lower excavation costs, smaller diameter pipes, no manholes to be built, fewer pumping and lift stations). The electrical costs to run the vacuum generators will usually be minor (about 30 to 40 kWh per person per year) (Ninham, 2004).

The implementation of sewerage system in the agricultural villages and rural areas of Egypt as a developing country has faced many problems in the design of the sewage network. The main problems in agricultural villages are: shallow ground water, flat landscape, narrow streets, crossing with existing waterways, and deep excavations and the need for pumping stations. As well the fees of cost return (benefits) are too low which imposes a tremendous challenge to select the most proper low cost technologies for sewerage transportation and treatment solutions (Abdel Gawad, 2007).

There is a thought that vacuum sewer system is much expansive than conventional sewerage systems and, hence is not suitable for developing regions. Recently, vacuum sewer, are trending to be used in wide spread but with some restrictions. Answering on which system better to be used, important aspects must be considered. Investment, operational, maintenance demands, environmental impacts, intensity of the served area and the terrain possibilities have a high priority as variables affecting on the suitable system to be chose (Stanko and Mahríková, 2009).

In this paper, cost comparisons between conventional and vacuum sewerage systems were done using statistical analysis. Correlation between the different affecting variables were obtained to know the most effective variables on the selection between both systems. Statistical predicting model using multiple regression analysis were extracted. Recommendation were deduced accordingly.

2. Methodology

2. 1. Statistics Analysis

In studies involving statistical analysis, it is important to characterize accurately “Population” and “Sample” under investigation (IBM, 2010). In this research, Egypt’s medium and small agricultural villages are “Population”. The chosen agricultural villages to be analysed is “Sample”. Sample size can be calculated using Eq. 1 (Daniel, 1999). Where n is sample size, Z is z statistic for a level of confidence, P is expected prevalence or proportion and d is precision. Z statistic for the level of confidence of 95 % which typically equals 1.96 (Naing et al, 2006).

$$n = \frac{Z^2 P(1-P)}{d^2} \qquad (1)$$

The Statistical analysis and testing are depending on variables type that could be dependent or independent variables. The dependent variable is the one to be studied as a function of other variables. Correspondingly, independent variables are those used to measure features manipulated, they represent variables believed to influence or predict a dependent measure.

The term “level of measurement” refer to the properties and meaning of numbers assigned to observations for each item. The four major classifications are nominal, ordinal, interval and ratio measurements. All affected variables are interval type which is defining as unit increase in numeric value represents the same change in quantity regardless of where it occurs on the scale (IBM, 2010).

Statistical tests are used to determine whether a relationship between the independent variable and dependent variable is statistically significant. In other words, it tests whether the independent variable can significantly explain the dependent variable (IBM, 2010).

Multiple regression is used to learn more about the relationship between several independent and a dependent variable (Stat Soft, 2011). Multiple regression requires a large number of observations. The number of cases (participants) must substantially exceed the number of independent variables using in regression. The absolute minimum is five times as many participants as independent variables and this is another method to get the sample size.

R is a measure of the correlation between the observed value and the predicted value of the dependent variable. The value "R^2" can be interpreted as the proportion of variation in one variable that can be predicted from the other. Thus an "R^2" of 0.50 indicates that we can account for 50% of the variance in one variable if we know values of the other. In essence, this is a measure of how good a prediction of the criterion variable we can make by knowing the independent variables. Adjusted "R^2" value gives the most useful measure of the success of the model (IBM, 2010).

2. 2. Affected Variables and Sample Selection

Taking into consideration Eq. 1 and the prevalence of the small and medium villages as 86% of villages in Egypt, the precision in this case will range between 10 – 15 %, consequently the sample size will vary from 20 to 46 villages. Sample was chosen with gross size of 28 villages which is respecting the range required for the sample. The maximum target population to be served is 10,000 capita. Different population and different areas were considered during sample selection.

The most variables affecting on choosing between conventional gravity and vacuum systems are population, area, terrain slopes, and the investment cost. As aforementioned, that variables types and level of measurement must be applied to identify the corresponding test. All variables are independent variables except the investment cost is the dependent variable. Average ground gradient was calculated and rated according to McDonald et al. 1990 (Dennis G et al, 2005).

2. 2. System Design and Variables Obtainment

For all 28 chosen villages, detailed hydraulic designs were held for both conventional and vacuum systems to determine pipes diameters, Pipes depths, and pumping requirements. Conventional sewer systems are typically designed for an economic life of about 30 years. Because of their high initial cost and relative inflexibility once installed (Richard and Duncan, 1980); for this the target year was assumed to be 2050 for designing of both systems. Egyptian codes were used in designing conventional sewerage systems, while German codes were used in designing of vacuum sewerage system. Terrain slopes were calculated for all roads include pipes and different component costs were calculated. The cost of mutual components are not considered such as the house connections pipes and inspection chambers. Then, Data became ready for complete statistical analysis.

3. Results and Discussion

Table 1 shows the raw data obtained from designing the 28 villages. For the agricultural villages under study, it is obviously that in any case the vacuum sewerage systems investment cost are lower than the conventional gravity sewerage systems even in the high density villages. It was found that the agricultural villages contain many of drains and canals and consequently the crossings under these waterways will be required, thus the cost of the gravity networks becomes so high. In vacuum sewerage

Table 1. Raw Data and Variables.

Village ID	Terrain Slope %	Population Capita	Area (ha)	Density (capita/ ha)	Gravity System Cost (million EGP)			Vacuum System Cost (million EGP)			Total Gravity System Cost (million EGP)	Total Vacuum System Cost (million EGP)	Diff. in Total Cost (million EGP)
					Networks	Manholes	Pump Station	Networks	Collection chambers	Pump Station			
1	-0.33	4,128	19.2	215	2.2	0.9	2.3	5.4	0.8	1.6	-1.0	3.8	-1.6
2	-0.15	10,380	40.8	254	3.6	1.8	3.0	8.4	1.8	3.1	-1.2	6.7	-1.7
3	Flat	6,959	32.4	215	3.9	2.8	2.9	9.7	2.1	2.2	-1.4	5.8	-3.9
4	0.95	3,655	18.4	199	2.4	1.5	2.3	6.2	1.1	1.2	-1.0	3.5	-2.7
5	0.23	2,981	12.6	237	2.1	1.0	2.3	5.5	0.8	1.4	-1.1	3.3	-2.2
6	0.07	10,555	36.6	288	5.5	3.9	3.3	12.7	2.6	2.0	-1.4	6.4	-6.2
7	-0.02	8,593	29.5	292	4.6	3.7	3.0	11.3	2.0	1.8	-1.3	5.4	-5.9
8	0.35	5,276	82.5	64	4.3	2.2	2.6	9.1	3.1	1.7	-1.2	6.2	-2.9
9	-0.01	2,207	31.1	71	1.1	0.5	2.2	3.7	0.5	0.7	-1.1	2.4	-1.4
10	Flat	2,632	26.9	98	1.2	0.5	2.3	4.0	0.6	0.8	-1.2	2.6	-1.5
11	-0.18	9,977	20.2	494	3.3	0.7	2.8	6.8	0.9	2.6	-1.1	5.2	-1.5
12	-0.15	10,350	26.2	394	3.3	1.4	2.9	7.7	1.3	2.4	-1.1	5.5	-2.1
13	-0.03	9,799	91.1	108	7.1	1.5	2.9	11.5	1.3	2.8	-1.2	5.8	-5.7
14	-0.23	1,462	10.1	145	2.0	0.5	2.0	4.5	0.5	0.5	-0.8	2.1	-2.4
15	0.27	5,570	50.1	111	4.4	2.8	2.6	9.8	3.0	1.7	-1.1	6.2	-3.6
16	-0.04	3,598	18.0	199	1.4	0.8	2.3	4.5	1.0	1.0	-1.0	3.3	-1.2
17	-0.06	2,816	16.7	168	1.7	0.8	2.2	4.6	0.9	0.9	-1.0	2.9	-1.7
18	0.16	8,624	56.8	152	3.9	2.4	2.9	9.2	2.5	2.8	-1.3	7.0	-2.2
19	0.06	6,789	63.3	107	5.1	3.8	2.7	11.6	3.3	1.3	-1.2	6.1	-5.5
20	Flat	5,105	38.7	132	3.4	1.7	2.6	7.7	2.2	2.1	-1.1	5.7	-2.0
21	-0.06	7,054	35.5	198	3.5	2.2	2.9	8.5	2.6	2.6	-1.4	6.7	-1.8
22	0.07	4,397	20.2	218	3.7	1.2	2.6	7.6	1.3	1.2	-1.2	3.9	-3.6
23	0.02	1,207	5.1	236	0.5	0.3	1.8	2.5	0.3	0.5	-0.7	2.0	-0.5
24	Flat	1,580	9.0	176	0.6	0.3	2.0	2.9	0.4	0.7	-0.9	2.3	-0.7
25	0.14	1,548	12.9	120	1.7	0.6	2.0	4.3	0.7	0.6	-0.9	2.4	-1.9
26	0.34	3,259	12.5	261	2.0	0.7	2.5	5.2	0.8	1.0	-1.2	3.0	-2.2
27	0.02	1,282	6.6	194	0.7	0.3	1.1	2.1	0.4	0.3	0.1	1.8	-0.4
28	-0.07	3,281	16.9	194	1.3	1.0	2.3	4.6	1.0	1.0	-1.1	3.1	-1.4

systems, no crossings are required, so the networks are considered the cost saving factor. Mostly, the cost of the vacuum collection chambers is higher than the cost of the manholes especially in high densities but in low densities the cost of both of them converge even the collection chambers' cost becomes less. In addition, the cost of the pumping stations is somehow higher than the vacuum station because that gravity pumps are installed at bigger depths than vacuum stations.

All data are inserted to the statistical analysis software SPSS version 18. Firstly it was found that the terrain slopes are not significant and are not influencing any component of both systems. Actually, this is logic because all the slope values in the agricultural villages under study could be considered as semi-flat. This is also explains the reason of gravity sewers highly cost. The prediction models were extracted from the software for each component based on the most significant affecting variables.

The most affected variables on gravity network cost were the population and area. For vacuum networks cost, the population had small significance resulting from the availability of certain range of using diameters (110-250 mm) thus wherever low or high densities exist, this range will be used. In the local marketing the prices of this range of diameters are so closely so the influence in the vacuum network cost due to the population is not high, especially a target population of 10,000 capita is used. Certainly, the areas have a great influence due to the effect of lengths increase.

Regarding manholes cost in gravity system, the population is more significance than the area. The population increase causes an increase in the diameters; the manholes on the large diameters are expensive. As well the flat terrain requires manholes with large depth. On the other hand, the vacuum collection chambers are depending mainly on the population. This is logic because the collection chambers are depending on the number of households which are increasing by population increase.

Both pump and vacuum stations are depending mainly on the population. Certainly the longest vacuum main is affecting the cost of the vacuum station due to the total losses of the lifts consumed, however all villages considered are small and medium with limited area which means non-significant lengths.

In summary, the total gravity system and total vacuum system costs are depending on the population and area. The predication models extracted from software SPSS based on the most significant affecting variables for both total gravity system cost and total vacuum system cost are shown in table 2 and are represented in Fig. 1.

In this study, the investment cost of vacuum system was found lower than the gravity system. However, this study is still under progress. The operational and maintenance cost is not studied yet for both gravity and vacuum systems. The operational and maintenance cost is expected to be higher in vacuum system.

Environmental impact assessment for both systems is under progress. It is expected that vacuum system will prevail in terms of environmental sustainability and public health. From the technical point of view, some disadvantages for implementation of vacuum system in developing regions is expected and to be studied. The disadvantages could be concluded in the following:

- Operation and maintenance of the system in remote areas may be a problem. From literature it would appear that the system can easily be kept operating successfully in developed countries. However, no literature found on the application of vacuum sewers in rural communities in developing countries. Outsourcing of operation and maintenance may be a viable alternative otherwise, social mobilization should take place to help the households to manage the system by themselves; but in this case, certainly training must be provided and regular visits from the responsible authority to be done.
- The fact that the system is unknown to sewerage practitioners in Egypt. This may mean that contract specifications may not be up to standard and inferior installations are constructed. This could be solved in case of aid of one of the major specialized companies in this field such as RediVac, AirVac, QuaVac and Roediger Vac Companies.
- Vacuum sewer system becomes less competitive the higher the population density gets. Cost saving factor is the network. High flows will require parallel vacuum sewer pipes and comparable huge vacuum stations.

Sewerage system selection should be a compromise between environmental, technical and financial aspects.

Table 2. Prediction Models and Affecting Variables.

System	Equation (Total cost in EGP)	R^2
Gravity System	$60768 + 67684 * A + 866 * Pop - 542 * A^2 + 0.82 * A * Pop - 0.046 * Pop^2$	0.81
Vacuum System	$351670 + 51453 * A + 1540 * Pop – 674 * A^2 + 7.96 * A * Pop - 0.1 * Pop^2$	0.86
Note: “Pop” is population in capita and “A” is Area in hectares.		

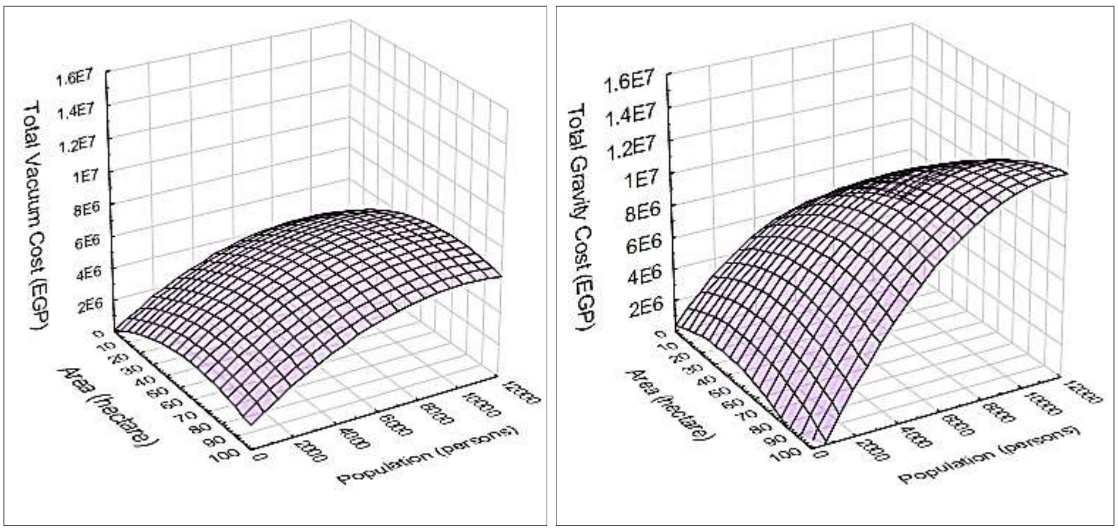

Fig. 1. Variables affecting on gravity system cost (left) and vacuum system cost (right).

4. Conclusion

Detailed hydraulic designs was held for conventional and vacuum sewerage systems in 28 chosen agricultural villages in Egypt. Cost comparisons for the components of both systems were done using statistical analysis. Statistical predicting model using multiple regression analysis were extracted. The total gravity system and total vacuum system costs are depending on the population and area variables. The investment cost of vacuum system was found lower than the gravity system. However, this study is still under progress. The operational and maintenance cost is not studied yet for both gravity and vacuum systems. It is recommended from the environmental point of view to construct the vacuum sewerage system. Depending on the local market during supplying of the construction equipment especially collection chamber will greatly decrease the investment cost. Capacity building and social mobilization will also play a great role in sustainability of this system. The challenge will be how to help the communities in management, operation and maintenance of the system. Awareness should be took place before starting the implementation to check their capability and responsibility. This will be the only way to serve the rural areas in the future and to decrease the pollution tends to the water resources. At the end, it is noteworthy that environmental sustainability and public health are more important than the financial aspects. Sewerage system selection should be a compromise between environmental, technical and financial aspects.

Acknowledgements

The authors are grateful to the Egyptian consultant firm “EnviroConsult” for providing them with maps, surveying, and design data for agricultural villages under study.

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