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Multi-segment trenchless technology method selection algorithm for buried pipelines

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ABSTRACT

There are many tools, models, and algorithms to aid in the selection of appropriate trenchless methods for pipeline installation or rehabilitation. However, one key concern is which method or technique provides optimum solution to the rehabilitation of multiple pipe segments rather than just a single pipe segment. Therefore, the searching criterion for an optimum decision support system is divided into two parts. First, the selection of the optimum method capable of solving the problem properly. Second, a simultaneous analysis of other parameters such as cost, time, and quality to improve the overall benefits of the project. It is observed that most of the real-world cases involves multiple segments in a single project. Therefore, an optimization of the solution must be made for those multiple pipe segments. Although use of different methods for each segment is a preferable solution, it may not be feasible in a wider consideration of project cost, quality, and time. Hence, one way to determine the optimal solution for multiple line segments is to minimize the number of methods and their anticipated total costs which include direct costs and social costs. This paper presents a mathematical approach to expedite the optimum solution by evaluating all of the trenchless technology methods capable of installing, replacing, or rehabilitating each pipe segment (a solution set) and minimizing the number of methods and their total costs.

1. Introduction

There are many tools, models, and algorithms to aid the decision support system for the selection of an appropriate method or technique of rehabilitation. The North American Society for Trenchless Technology (NASTT) developed a set of methods, materials, and equipments for the rehabilitation and new installation of underground infrastructure that incur minimum disturbance to the adjacent areas and related businesses (Allouche, 2001). However, the key concern is which method or technique provides optimum solution to the rehabilitation of sewer networks. Therefore, the searching criterion for an optimum decision support system is divided into two parts. First is the selection of the optimum method capable of solving the problem properly. Second, a simultaneous analysis of other parameters is performed that involves cost, time, and quality to improve the overall benefits of the project.

Based on application to the specific fields, decision support models can be classified into three categories, namely (1) general models, (2) wastewater models, and (3) water models (Matthews et al., 2012, 2011). General models combine both the wastewater and water networks. The two general models from the literature are the Trenchless Assessment Guide for Rehabilitation (TAG-R), developed by Matthews (2010) and the Renewal Engineering Selection Tool (REST). TAG-R directly collects input from the data available in the planning phase and provides the technically viable alternatives, whereas REST provides the technically viable alternatives along with a ranking factor for each. Two models developed outside on the U.S. for the decision support of wastewater were the Computer Aided Rehabilitation of Sewer Networks for Sewers (CARE-S, Baur et al., 2005, 2006) and a Geographical Information System (GIS) based decision systems (Halfawy et al., 2008, 2009). For the decision support of water networks, the proposed two models were CDSS (Comprehensive Decision Support System) by Deb et al. (2002) and a model developed by Ammar et al. (2010).

A multi-criteria decision support system was developed by Matthews (2010) to select the rehabilitation, construction, and maintenance technique for buried pipes. The Culvert Renewal Selection Tool (CREST) was developed to select the optimal renewal technique in terms of cost, expected design life and productivity for varying culvert materials, diameters, and defects (Jin et al., 2015; Jin, 2016). Other

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multi-criteria selection tools include models developed by Park and Kim (2013) and Kleidorfer et al. (2013). However, there is not yet a method available that can address the direct cost, social cost, and carbon footprint cost in a multi-criteria decision making process for multi-segment projects. This is resonant with the findings of Matthews et al. (2011), who noted that there is no standalone tool currently available which is sufficient to evaluate the sewer projects on segment-by-segment basis.

In addition to tools and models, decision support algorithms play a key role for the selection of optimum method(s). The approaches to decision support systems and type of algorithms used in developing these tools vary based on the type of problem it needs to address. The predominant algorithms are (1) fuzzy set theory, (2) expert systems, (3) neural networks, and (4) genetic algorithm (Allouche, 2001; Nishiyama and Filion, 2013). Fuzzy set theory is used to analyze uncertain and imprecise information related to the optimal renewal method selection. It is comprised of numerical data and a set of equations while the expert system and artificial neural network (ANN) approaches belong to the artificial intelligence arena. The expert systems apply computer codes to select a simplified solution of a complicated problem by using the cumulative knowledge and experience of several experts. ANN imitates the human brain, and can be trained to recognize patterns (Clair et al., 2012). The expert algorithm follows the IF-ELSE loop along with couple of thumb-rules, whereas, the neural network builds a relationship between input and output by assigning a weighing factor to multiple interconnections. Finally, the genetic algorithm (GA) is a technique that mimics the biological process of reproduction, inheritance, selection, mutation, and crossover to solve complex optimization problems as it relates to buried infrastructure renewal scheduling (e.g. Alvisi and Franchini, 2006; Giustolisi et al., 2006). GA consistently becoming an avenue of research for the optimization of multi-segments as well as multi-objectives for a project. GA can optimize both single criteria optimization, through Goldberg algorithm (Goldberg, 1989) and multi-criteria, through Pareto optimal front (Halfawy et al., 2009).

Multi-criteria multi-segment projects are observed in most real-world cases. Construction companies are striving to complete their projects by minimizing the time and costs involved in it and maximizing the productivity. Although use of different method for each pipe segment is a preferable solution, it may not be feasible in a wider consideration of project cost, quality, and time. Hence, one way to determine the optimal solution for multiple line segments is to minimize the number of methods and their anticipated total costs that include direct costs and social costs (Matthews, 2010).

In addition to direct cost and social costs, carbon offset or carbon cost is a quantifiable parameter that can be included in the analysis. Precisely, carbon offset not only has impact on the environment but it also calculates the cost per ton of carbon emission. Because the environment and sustainability is a key concern for many of the stakeholders associated to construction and rehabilitation of buried pipelines, the interest in carbon offset is neither negligible nor insignificant. Therefore, optimal solution to multi-segment renewal decisions should include cost (direct, social, and carbon) reduction.

Whatever we build or construct affect the environment either positively or negatively. The negative effects of construction such as noise and air pollution are borne by the community not the contractual parties. Environmental impact and sustainability involves a great deal of loss. For example, the noise pollution certainly concerns people and surrounding properties, and reduce the productivity and happiness of everyone. Likewise, air pollution occurs from various gases and carbon dioxide emission through machineries and equipments used in construction. Furthermore, traffic delay which constitutes 50% of the social cost, increases the fuel consumption of vehicles due to extra time of travel.

2. Literature review

Multi-segment optimization: A segment is a combination of individual (or group of) mainlines, manholes, and laterals. Based on the name and numbers, the segments are divided into three categories: (a) segments that have one mainline, manhole, or lateral separately, (b) segments that have one mainline and one or two manholes, and (c) segments that have one mainline, one or two manholes, and one or more laterals. A multi-segment generally consists of a number of segments.

According to Goldberg (1989), optimization is the process of seeking the best. The searching of best performance or solution towards an optimal point is a two-lane road. First, an optimization strives to improve the process; second, it drives to reach the optimal point. Traditionally, optimization means convergence that leads to an optimum method. However, it fails to interpret the interim performance and related improvements properly. Therefore, in many cases a global optimization becomes hard to obtain. The phenomena of natural selection process can be mimicked here, as its goal is to select optimum method by seeking continuous improvement as well as goodness-of-fit.

The prime objective of multi-segment optimization is to select the optimal method(s) for rehabilitation/repair of the respective pipe segments. In this regard, the optimization process of the multi-segment can be best explained by using it to evaluate a real world example that involves multiple line segments needing to be replaced or rehabilitated. The three line segments used to show how this process can be used were actual construction projects undertaken by the City of Edmonton, Alberta, as part of their Southside Sewer Relief program in the 1990s (Parhami, 2004). All three segments were analyzed with TAG and TAG-R to determine which methods were technically viable (Matthews 2006, 2010). Details are described in the case history section.

Multi-Criteria Optimization: The multi criteria optimization can be conceptualized from the difference between multi criteria and single criteria optimization. Whilst multi criteria searches for the best compromise between several objectives in the search space (Abraham and Jain, 2005; Jaszkiewicz, 2002; Coverstone-Carrroll et al., 2000); the single criteria searches for a single optimal solution such as cost, quality or time (Abraham and Jain, 2005; Coverstone-Carrroll et al., 2000). The advantage of multi-criteria optimization is that it can define complex problems better by defining every individual criterion. However, there are not enough well developed techniques to describe multiple optimizations (Abraham and Jain, 2005). Moreover, the problem solving process is cumbersome and time consuming, in comparison to single criteria optimization.

Although multi-criteria optimization has some shortcomings, it is still a preferable choice due to the simultaneous optimization of multiple objectives. For example, completion of a successful project is grounded in the optimization of cost, quality, and time. Optimization of these three parameters is doable by using the multi criteria analysis. However, it may not be possible to optimize these three parameters by single criteria analysis. Although, the cost and time parameter is quantifiable in terms of money, there is hardly any unique way to calculate all the aspects of quality parameters.

However, it is not always necessary in multi criteria analysis that the best solution set represents the best of every criterion, but rather it generates the most efficient solution sets (Jaszkiewicz, 2002). Therefore, the best solution can be a combination of best of one criterion, second best of another and so on. According to Abraham and Jain (2005) the optimal result is likely to be obtained if other solutions of the search space do not dominate it. This type of non-dominated solution is termed as Pareto-optimal. In multi criteria analysis, Pareto-optimal set supports the real world decision making process by generating the best possible outcome. Recent works that use multi-criteria optimization process include for example the work of Fontana and Morais (2013) who developed a rehabilitation model for a water network that maximizes the number of rehabilitated leaks while minimizing the costs involved, and the work of Scheidegger et al. (2013) who developed a

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