Transportation Research Part E 113 (2018) 38–55

Contents lists available at ScienceDirect

Transportation Research Part E

journal homepage: www.elsevier.com/locate/tre

Network-based optimization modeling of manhole setting for pipeline transportation

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ARTICLE INFO

Keywords:
Pipeline transportation
Manhole setting
Topological sort

ABSTRACT

This study proposes a network-based methodology for the optimization of manhole setting problem, which is a key component of pipeline transportation. The objective is to minimize the total social cost which involves the construction cost and the maintenance cost including the negative impact of manholes on the ground transportation. We first consider a special model which is efficiently solved by a topological sort-based approach. Later, we build a generic model and prove it to be NP-hard. A metaheuristic method is developed to obtain good-quality solutions. Finally, the models and solution methods are validated by numerical examples.

1. Introduction

Pipeline transportation is an integral part of the urban transportation system, which carries the transportation of some liquids and gases (e.g. sewage, natural gas) through pipelines (Geem, 2006; Chebouba et al., 2009; De Jong et al., 2013; Kazemi and Szmerekovsky, 2015; Al-Haidous et al., 2016; Lee et al., 2016; Koza et al., 2017; among many others). As one of the most common modes of pipeline transportation, sewerage transports domestic wastewater or surface runoff (rainwater, stormwater, meltwater) from residential, commercial and industrial areas to the sewage treatment plants or some locations of discharge into the environment. It encompasses infrastructures such as pipes, manholes, pumping stations, and screening chambers of the combined sewer or sanitary sewer (Spellman, 2003). Most of these components are located at the underground space, and only manholes can be seen by the general public. A manhole is the top opening to an underground utility vault which connects other sewerage infrastructures, as illustrated in Fig. 1. Due to the development of inspection technique and trenchless technology, manholes are available to inspect and perform maintenance on the adjacent sewer pipes that are buried in the subsurface.

Manholes play a pivotal role in the sewerage system. Currently, a number of studies have been conducted on the project cost management with respect to manholes, because they require a huge amount of investment (McGhee, 1991; Tsagarakis et al., 2003; Read, 2004; Shank et al., 2005; Haller et al., 2007; Walker, 2009). Though these studies mainly discussed manholes from the perspective of structure engineering and environment, they are beneficial to quantify the cost of manholes. Specifically, the project cost of manholes can be decomposed into two parts, namely the construction cost and the maintenance cost. The construction cost is mainly influenced by the soil type beneath streets, depth of sewer pipes and manhole size. Regular maintenance is essential to prevent pipeline clogging and deterioration, which includes repair, renovation and replacement activities (Fenner, 2000; Van der Hoop,

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https://doi.org/10.1016/j.tre.2018.01.010
Received 8 April 2017; Received in revised form 10 January 2018; Accepted 11 January 2018

(a) Manhole cover (b) Repair and maintenance (c) Underground space

Fig. 1. Illustration of the manhole.

2010). In addition, the damage of manhole covers[1] may become deteriorated due to frequent pressure from the ground transportation (e.g. bicycle and automobile), and this influencing factor is also considered in the maintenance cost.

When manholes are under maintenance (see Fig. 1b), they temporarily interrupt the flow of traffic on the road segment and reduce the capacity. Some studies proposed several road traffic control strategies to alleviate the negative effects of this type of special events (Papageorgiou et al., 2003; Sheu, 2007; Wojtowicz and Wallace, 2010; Atwater et al., 2014; Xiang et al., 2016). Furthermore, if the manhole covers are not appropriately installed or maintained, they may give rise to safety hazards and sometimes even accidents (Meng and Qu, 2012; Zhou et al., 2017). For instance, Chang (2014) proposed a classification and regression tree model to analyze the influence of manhole covers on motorcycle drivers' maneuvers. Results show that nearly half of motorcycle drivers decelerated or changed their driving track when passing a manhole cover on the vehicle lane. Pavement condition over the manhole cover and the size of manhole cover can significantly affect motorcycle drivers' maneuvers. Wu et al. (2015) obtained analogous results of bicycle behaviors when manhole covers are located at the bicycle lane. These studies demonstrate that the effect of manholes is an important issue in the field of ground transportation as well as pipeline transportation.

In urban areas, the underground space is becoming increasingly crowded due to the constant construction of metro transit network, parking garage, and subsurface infrastructures of pipeline transportation associated with other modes of pipeline transportation (e.g. water supply, natural gas). Therefore, it is essential to optimize the manhole setting in order to make the utmost use of scarce underground resources, and meantime can possibly reduce the detrimental impact on the operation of ground transportation. Previous studies have developed methods to estimate the project cost of manholes and their adverse effect on the ground transportation, whereas most of them studied one manhole or manholes of a single pipeline. In practice, the sewerage system of a certain city area usually has many sewer pipelines. To optimize the infrastructure management of all these pipelines simultaneously is an appropriate option in order to further cut down the costly expenditure. Currently, different management science approaches have been proposed to investigate various issues pertinent to transportation service design and management (Dorsey, 2005; Sheu, 2010; Andrijcic et al., 2013; Habibian and Kermanshah, 2013; Chen et al., 2017). Yet, studies that exclusively discuss the network-based manhole setting from the perspective of transportation management are limited.

Manhole setting problem (MSP) is a problem that selects a set of candidate manholes for construction, which belongs to the realm of discrete optimization. MSP parallels many other transportation problems related to discrete optimization, such as transit network design (TND). As of now, there has been a fruitful development of models and solution techniques to address TND (e.g., Ceder, 2007; Currie and Tivendale, 2010; Szeto and Jiang, 2012; Currie et al., 2013; An and Lo, 2014; Jin et al., 2014; Fu et al., 2014; Chen et al., 2015; Fu and Lam, 2016; Liu and Zhou, 2016). TND determines the stop location choice of transit routes. Its objective is usually to minimize the total cost of two stakeholders (passengers and operating agency), such as passengers' travel cost and operational cost. Comparatively, the construction cost and the maintenance cost of transit stops are less important than the above cost terms, sometimes even omitted from the objective function. In MSP, the manhole can be constructed at the intersection of several sewer pipelines. It is a bit different in TND that the intersecting node of two transit routes is one signalized/unsignalized intersection, which is not a stop where transfers occur. Instead, only stops within the shared route segment of some routes can be used by passengers to transfer. Furthermore, the other distinction of two problems is that TND needs to consider network supply and demand simultaneously, which usually present the structure of a bi-level programming or a leader-follower game (Liu et al., 2013; Szeto and Jiang, 2014; Ceder et al., 2015; Chen et al., 2016). Due to such a complicated feature, most problems in existing studies are NP-hard, and various heuristic and metaheuristic methods were developed to obtain potentially good solutions. In contrast, MSP mainly focuses on the supply side which decreases the complexity of the problem, and hence it is possible to propose exact solution methods to design the optimal manhole setting.

The above comparison between two problems indicates that the extant TND models in the literature are not available to directly address the manhole setting problem. Furthermore, the manhole setting of sewer pipelines are independent while sometimes are dependent on other sewer pipelines. Therefore, the network-based MSP may present various computational complexities. To the

[1] A manhole cover is a removable plate forming the lid over the opening of a manhole, which prevents anyone or anything from falling in, and keeps out unauthorized persons and material.