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Layout optimization of natural gas network planning: Synchronizing minimum risk loss with total cost

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ABSTRACT

The synchronization of the minimum risk loss and total cost of natural gas pipeline networks at the planning stage is discussed in this article. Herein, new procedures for optimizing layout are proposed to minimize the investment cost, operation expense, and the risk loss of the pipeline network. The procedures include two crucial steps: the first step is fitting two risk cost functions (i.e., leakage risk cost function and corrosion risk cost function), and the second one is achieving the optimal layout by using the risk cost functions as the edge weight of the minimum spanning tree algorithm. The suggested method is applied in three different real cases, leading to three distinct optimal layouts, which are more suitable than that calculated using intelligent algorithms for practical engineering. Then, two optimal strategies for pipeline network layouts are presented. Different applications that respectively focus on the leakage risk cost for urban areas and the corrosion risk cost or leakage risk cost for suburban areas are shown in the above two strategies. These strategies realize a 6.9–21% greater economic benefit than that of the shortest layout.

1. Introduction

The investment and operation costs of natural gas pipeline networks are commonly considered important aspects of the total investment. Moreover, environmental and social economic losses should not be ignored at the planning stage of the network design because the losses caused by natural gas leakage are so huge during construction and operation stages. Hence, guaranteeing the gas transmission to individuals with minimum risk loss and effective cost necessitates optimizing the pipeline network. Safety and reliability at the operation stage of pipeline networks have been extensively treated previously for their important roles in risk loss of natural gas transportation (Rios-Mercado and Borraz-Sanchez, 2015).

Pipe diameter and layout are calculated based on the flow horizon and node pressure horizon (Hanbing et al., 2015), respectively, which is a common optimization method in natural gas network design that has led to a great many optimization models and algorithms in recent years. The optimization method usually consists of two steps: firstly, the shortest pipeline layout or minimum pipe laying cost must be identified; secondly, the appropriate pipe diameter with the lowest possible metal cost is determined based on the identified layout (Jin and Wojtanowicz, 2010). Operation optimization is a hotspot of the common optimization, and it refers to some parameters, including pipe diameter, pressure and quantity of the compressor, whereas these parameters are often calculated according to the identified layout. Üster and Dilaveroğlu (2014) applied a heuristic random search optimization method (Valipour, 2016) to model an existing network over a long-run planning horizon with optimum discounted operation and capital costs. In Bernier's work (2010), a multi-objective model was proposed by combining a process flowsheeting model and a separate process-integration model without considering the risk loss. Although various optimization models and improved algorithms have been developed (e.g., Khan and Lee, 2013; Mohammad et al., 2015; Pfetsch et al., 2015; El-Sheikh, 2013; Sanchez-Ubeda and Berzosa, 2007), risk loss was always ignored (Schmidt et al., 2015; Zhu et al., 2001; Valipour et al., 2013). As mentioned previously, safety and reliability are widely considered at the operation stage of pipeline networks (Rios-Mercado and Borraz-Sanchez, 2015; Schmidt et al., 2015), while relevant studies performed at the layout or planning stage are rather limited. According to the data from developed countries' surveying bureaus, the economic loss caused by corrosion is 2–4% of annual

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gross national economies (Gangya et al., 2007). Every year, economic losses worth 2.8 × 10^{11} RMB are caused by corrosion, which has become a critical factor in influencing the safety and reliability of pipeline operation (Borraz-Sanchez and Haugland, 2013). Additionally, the corrosion has even brought about a large amount of social issues (Ossai et al., 2015).

Synchronizing the layout, risk loss and planning stages in one model is challenging because the mathematical optimization of natural gas pipelines is difficult to develop. Previous approaches usually minimized the risk loss by employing network security assessment technology and integrity management technology, which are based on the deterministic layout (Stalheim, 2011; Suresh et al., 2008; Reitenbach et al., 2015; Wu et al., 2007), and therefore synchronization of the risk loss and the planning stage could not be achieved.

Overall, three limitations exist in previous studies according to the above discussion: 1) common total optimization or operation optimization is created only after the layout is created; 2) Optimal layout is obtained by using intelligent algorithms or conventional optimization algorithms, which are not consistent with the actual pipeline laying path; 3) Common total optimization does not consider economic loss caused by environmental disruption or casualties derived from the risk factors.

Synchronizing total cost, risk loss and the layout at the planning stage could not be found in any of the literature. The objective of the present work is to propose the problem of new layout optimization, in which new procedures are presented and the two risk costs are developed based on the above three limitations. In addition, two strategies for optimizing the pipeline network layout are obtained by applying the procedures.

2. Problem statement of the new layout optimization

The problem statement of the new layout optimization is to synchronize the minimum of risk loss and total cost of natural gas pipeline networks at the planning stage. The mathematical model and the calculation procedures, which constitute the crucial framework of this problem, are described in the following subsections.

2.1. Mathematical model

The layout optimization presented by Sanaye and Mahmoudimehr (2013) is committed to minimizing total costs (containing investment and operating costs). However, without risk loss, the layout optimization results are not entirely consistent with practical application, which is mainly due to the crossover and mutation of the genetic algorithm (GA) program. GA is based on the random combination of one group of network data, and hence the as-obtained optimal layout is not suitable for pipe laying. In our work, a feasible layout decision is obtained by employing graph theory because the original and input data are derived from the actual pipeline laying path.

The edge weight in this article is expressed using cost functions for leakage risk and corrosion risk according to graph theory, in which the edge weight of the network graph can be expressed by different types of practical data. The corrosion prevention cost, corrosion risk loss cost, leakage risk loss cost and total investment cost are used in the corrosion risk cost.

Thus, the two costs (i.e., leakage risk cost and corrosion risk cost) can be summarized by the following formulas.

$$\text{Leakage risk cost} = \text{leakage risk loss cost} + \text{investment cost} \tag{1}$$

$$\text{Corrosion risk cost} = \text{leakage risk loss cost} + \text{investment cost} + \text{operation cost} \tag{2}$$

The investment cost and operation cost per unit length of pipeline include material, labor, installation, purchase and transportation costs, which depend on the pipe length, pipe diameter, and electricity used by the compressor stations. The leakage risk cost, the economic loss caused by social environmental consequences and casualties, has been substantial in recent years because accidents have happened frequently with the increasing number of pipeline transmission networks that have been built. Particularly, these costs are calculated by using the net present value of real project. Hence, it is not necessary to estimate the input parameters for fitting the two cost functions. Moreover, the more comprehensive these costs are, the more accurate the risk cost function will be. Equation (1) only emphasizes the leakage risk loss cost that is included in the above two functions, as it is the main difference between urban and suburban areas.

2.1.1. Risk cost function

On the one hand, the leakage risk cost should be the focus of middle and low pressure pipeline networks in urban areas because environmental economic losses caused by corrosion and third party damage are very large. On the other hand, the corrosion risk cost should be the focus of long-distance high pressure pipeline networks in suburban areas because the leakage risk loss cost is too small to be concerning (Biscan and Loncar, 2010). The corrosion risk cost includes two aspects: one is the pipeline corrosion risk cost during construction and operation periods, and another is the economic loss due to corrosion leakage. The two aspects are associated with the pipe network's geographical environment, which is often affected by random disturbances, such as the flow of people, surrounding pipelines and buildings around the pipeline. Therefore, the risk levels of soil corrosion can be used as independent variables to fit the corrosion risk function (Zhiping et al., 2014). Soil components are often treated as an index in buried pipeline corrosion because buried pipelines are exposed to various types of soil in different regions (Wu et al., 2014) .

Both corrosion risk cost and leakage risk cost vary with pipeline soil environment changes, and two chemical components of the soil, i.e., the resistivity x and the moisture content y, are defined as the independent variables of the cost function (Valipour and Montazar, 2012). Thus, the form of leakage risk or corrosion risk functions is given as follows:

$$z = z0 + a^*\cos(x/w1) + b^*\sin(x/w1) + c^*\cos(y/w2) + d^*\sin(y/w2); \tag{3}$$

where z is the risk cost; x is the resistivity; y is the moisture content; and w1, w2, w3, and w4 are calculated based on the data (Table 1) fitted by the origin 9.0 version. Equation (3) expresses the basic relationship of the total cost and the risk loss by using soil constituents as parameters (i.e., x and y).

Equation (3) is the reasonable functional form to calculate the two risk costs because both the convergence and the minimum fitting error of this equation's form are better than others. Although the error is not as ideal as that calculated by Einstein's energy equation, it hardly affects the new procedures and the two layout strategies proposed in this work.

Parameters are solved by algorithm fitting, and the closer that the multiple correlation coefficient R is to ±1, the better the as-fitted result. R is calculated by using the following formula: