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Earth pressures on the trenched HDPE pipes in fine-grained soils during construction phase: Full-scale field trial and finite element modeling

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ABSTRACT

High density polyethylene (HDPE) pipes have been widely used in civil engineering applications. The peaking deflection of the buried HDPE pipes caused by the compaction of the pipe sidefill during the construction phase is not considered in the current pipe design standards. Fine-grained soil may be an alternative backfill when relative high quality coarse-grained soil is absent in-situ or difficult to transport from a long-distance away in urban areas. The effect of construction on the earth pressures around HDPE pipes buried in fine-grained backfills has not been well understood. In this study, a full-scale field trial was undertaken to monitor the earth pressures acting on HDPE pipes buried in fine-grained soils during the construction phase. Three HDPE pipes with norminal diameters of 600, 600, and 300 mm, respectively, were used in the field trial. Numerical modeling which was able to consider the peaking deflection was conducted to investigate the effects of pipe diameter, pipe stiffness, degree of compaction of the backfill, and trench width on the earth pressures acting on the pipes. The measured earth pressures and deflection were utilized to verify the effectiveness of numerical modeling procedures. The finite element analyses indicated that the trench width had a more significant effect on the earth pressures, as compared to other factors. Two empirical equations were proposed, based on the numerical results, for predicting the earth pressures at the top and the springline of the pipes during the construction phase. The validity of the proposed equations was evaluated using the field data obtained from both this study and published studies.

Introduction

High Density PolyEthylene (HDPE) pipes are increasingly used as an alternative to reinforced concrete pipes, corrugated metal pipes, and cast iron pipes in practice due to their light weight, lower cost, and chemical resistance. So far, 90% of the natural gas pipeline and 60% of water supply pipeline are HDPE pipes in developed countries [47]. However, civil engineers are facing two problems in the design of buried HDPE pipes: (1) peaking behavior induced by the side fill compaction is not considered in the current design standards (e.g., AASHTO [1] method and CECS [10] method) which could affect the load distribution around the pipe during installation and under loading [36,35,3,29,47,21]; and (2) fine-grained material is occasionally used as backfill material for HDPE pipes in urban areas when good soil is not available. However, some empirical parameters are not valid for fine-grained material, for example, the shape factor to calculate the pipe combined strain in the AASHTO method [1].

Several empirical and theoretical design methods for earth pressures at the top of the pipe have been proposed [27,44,32,36,35,37,40,12,8,9,52]. Marston and Anderson [27] considered the reduction in the overburden stress at the pipe top due to the friction between the soil cover and the trench wall, which was referred to as “soil arching”. Marston [28] investigated earth pressures on pipes in embankment condition and suggested using compressible materials overlying the pipes which could result in soil arching effect to minimize the earth pressure on the pipe. Spangler [45] proposed approaches to calculate the earth pressure on pipes buried in an embankment in complete and incomplete projection conditions (i.e., soil arching effect occurred in the whole or part

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of the soil cover of buried pipes in terms of thickness). Meyerhof and Adams [33] proposed a calculation formula for earth pressure on buried pipes similar to the Marston-Spangler theory with an assumption of the lateral earth pressure coefficient as 0.95 at the trench wall. The American Water Works Association [26] proposed a simplified approach based on the Marston-Spangler theory. Frustum calculation method was proposed to calculate live loads induced stresses acting on the pipes [30,25]. A simplified method was proposed to calculate the distributed stress on the buried structures [18,19,17]. However, the Marston load theory-related equations proposed for trenched pipe were only suitable for rigid pipes [39,34].

Several methods have been proposed to evaluate the structural responses of buried flexible pipes [44,48,31,1,10,16]. Spangler [44] assumed passive horizontal earth pressure distributed as a parabolic shape at pipe sides and proposed Iowa formula to calculate the deflection of flexible pipes. Watkins and Spangler [48] indicated that the modulus of passive resistance of the soil defined in Iowa formula was not a real soil property. They introduced a parameter called the modulus of soil reaction to modify the Iowa formula. Based on the modified Iowa formula, McGrath [31] considered the effect of the hoop compression of the flexible pipe to calculate the vertical deflection of the pipe caused by the overburden earth pressure. AASHTO LRFD Bridge Design Specifications have been widely used in the design of buried HDPE pipes in the United States of America. This standard could be used to calculate the earth pressure on the top of the pipe for calculation of the pipe strains by the soil prism load multiplied by the Vertical Arching Factor (VAF) determined by empirical correlations considering the pipe-soil interface roughness [1]. The value of VAF was derived based on the assumption that the pipe was surrounded by isotropic elastic continuum and subjected to uniformly distributed loads. In other words, the effect of the friction forces at the interface of the backfill and trench wall on the trenched pipe was ignored. China Association for Engineering Construction Standardization [10] and Federal Construction Council [16] simply assumed that the earth pressure acting on the top of buried flexible pipes was equal to the overburden stress of the soil cover. Shen et al. [42,43,41] indicated that transferring of shearing deformation along the longitudinal direction of tunnel would induce diameter change and load redistribution. Wu et al. proposed a model to estimate the traffic loading induced deformation of tunnel [49] and a longitudinal structural model to evaluate the interaction between lateral deformation and longitudinal behavior of tunnel [50,51].

Sargand et al. [35], McGrath et al. [32], and Masada and Sargand [29] pointed out that the flexible pipe would deform into a shape like a vertical ellipse due to the compaction on the side fill, which was referred to as "peaking behavior". This diametrical distortion phenomenon was also found in jacked pipes during construction [13]. The increase in the vertical diameter of the pipe caused by the peaking behavior was so-called as peaking deflection. However, in the current design methods (e.g. [1,10] for flexible pipes, the deformed shape of pipes was assumed as circular when the backfilling was equal to the pipe top level; in other words, the peaking behavior was ignored. It is well-known that the soil arching occurred above the pipes was associated with the flexural deflection and circumferential shortening of the pipes [36,35,38]. With the ignorance of the peaking deflection, the deflection of the pipe would not be accurate and this could influence the load distribution around the pipe. Therefore, the peaking deflection is necessary to be included in the design method.

HDPE pipes were commonly buried in coarse-grained soils including gravel and sand. However, coarse-grained soils may not be available in urban areas due to high cost of long distance transportation. Therefore, fine-grained soils were also recommended as backfill material under this specific condition [10]. Previous studies focused mainly on the HDPE pipes buried in coarse-grained soils, whereas studies on the pipes buried in fine-grained soils were very limited.

Full-scale field trials have been widely used to investigate the earth pressure of buried HDPE pipes. Adams et al. [2] studied the performance of a 600-mm diameter corrugated HDPE pipe under a 30-m high soil fill, and found that the vertical earth pressure measured at the top of the pipe was only 23% of the geostatic pressure. McGrath et al. [32] conducted a series of full-scale field trials to investigate earth pressures around the buried HDPE pipes during the pipe installation. They reported that the compaction effect on the sidefill caused a decrease of the pipe invert pressure. Sargand et al. [36,35] indicated that the measured earth pressures at the top of HDPE pipes installed in the sand and crushed limestone backfills were 33% to 54% of the geostatic pressures. They found that the soil-pipe interaction zone extended to a place only one pipe diameter above the pipe.

Numerical modeling, as an effective tool, has also been used extensively to investigate the earth pressure on buried HDPE pipes. Katona et al. [23,24] developed a software CANDE (Culvert ANalysis and DEsign) to analyze the buried HDPE pipes. McGrath et al. [32] reported that the change of pipe deflection simulated by CANDE was in substantial agreement with the field observation by considering the soil compaction. Dhar et al. [14] conducted two-dimensional finite element analysis to investigate the performance of buried HDPE pipes. They reported that the soil with low stiffness in the haunch zone could result in stress concentration of the pipe wall. Elshimi and Moore [15] proposed a modification factor, K_n in the numerical modeling of side fill compaction to consider the soil kneading and repetitive cycles of compaction during placement of the sidefill.

In this study, a full-scale field trial was conducted to investigate the earth pressures on HDPE pipes buried in fine-grained soil during the construction phase. A numerical study using the two-dimensional finite element (FE) method, which was able to consider the peaking deflection of pipes, was employed to investigate the effects of pipe diameter, relative flexure stiffness, and trench width on the earth pressures at the top and springline of the pipes. Based on the soil arching ratio (i.e., the ratio of the measured earth pressure to the overburden earth pressure) at the top and the springline of the pipes obtained from the numerical modeling, two empirical correlations were proposed to predict the earth pressures at the top and the springline during the installation of the pipe. Field data in both this study and the published studies were used to verify the proposed empirical correlations.

Field instrumentation and measurements

Site conditions

The field trial site was located in the Xinzhuang bridge construction site, Yixing City, China. The groundwater table was 2.5 m below the ground surface during the test, which was lower than the trench depth. Therefore, the groundwater effect on the performance of the pipes was not considered in this study. Physical properties of the native soil are shown in Table 1. Based on the Unified Soil Classification System [4], the native soil was classified as low plasticity clay (CL).

2.2 Testing pipes, instrumentation, and backfill material

Three double-wall corrugated HDPE pipes labeled as P1, P2 and P3, with norminal diameters of 600, 600, and 300 mm, respectively, were adopted in this field trial. The profile of the pipe wall is shown in Fig. 1, and Table 2 summarizes physical properties of