Full-Scale Field Tests on Soil Arching Triggered during Construction of Shallowly Buried HDPE Pipes

M. Zhou[1], Y. J. Du[2*] and F. Wang[3]
[1,2,3]*Institute of Geotechnical Engineering, School of Transportation, Southeast University, Nanjing, China*
E-mail: duyanjun@seu.edu.cn

ABSTRACT: Soil arching significantly affects earth pressures around and above high-density polyethylene (HDPE) pipes in the construction phase. However, few studies have systematically addressed the change of soil arching with respect to soil cover thickness during the installation of HDPE pipes. This paper presents full-scale field investigations on the soil arching above and around three HDPE pipes buried shallowly in trenches. The results demonstrate that the soil arching developed in the backfill above the pipes is getting significant with increasing soil cover thickness. At a given soil cover thickness, more notable soil arching is found at a position closer to the pipe crown. The measured earth pressures acting on the pipe crown are compared with those estimated by the Marston load theory. It is found that the crown earth pressures estimated by the Marston's trench equation and embankment equation are 8% to 32% and 2% to 14% respectively higher than those obtained from the field tests. The results suggest that a threshold trench width is likely to exist when the Marston load theory is used for calculating the earth pressures on the top of HDPE pipes buried in the trench.

KEYWORDS: HDPE pipe, Field test, Soil arching, The Marston load theory.

1. INTRODUTION

Shallowly buried high-density polyethylene (HDPE) pipes have been used widely in engineering practice. Understanding the soil-pipe interaction is essential for predicting the long-term performance of the HDPE pipes in the serve time. The behavior of shallowly buried HDPE pipes subjected to traffic and surface loading has been investigated extensively in previous studies (Dhar et al. 2004; Talesnick et al. 2011; Terzi et al. 2012; Corey et al. 2014). These studies show that the pipe deformation and earth pressure acting on the pipe are significantly controlled by the magnitude of the live load, relative stiffness of the pipe to the surrounding soil and overburden soil cover thickness. Nevertheless, the change in the earth pressure with respect to the soil cover thickness and consequent influence on the pipe deformation in the construction phase (hereinafter referred to as installation effect) have not been well addressed. Previous studies show that the installation effect has significant impact on the performance of buried flexible pipes during service time (Adams et al. 1988; Sargand and Masads 2000; Sargand et al. 2008). For instance, Arockiasamy et al. (2006) indicated the magnitude of the vertical deflection of the HDPE pipes in construction phase could even reach approximately the same as that caused by the traffic loads.

A proper measurement or estimation of the earth pressure on the top of the pipe in the construction phase is very crucial for assessing the deflection of buried pipes. Moser and Folkman (1990) showed that the ring deflection of a flexible pipe transferred the major portion of the vertical soil load to the surrounding soil due to soil arching above the pipe. They indicated that soil arching had exerted a tremendous influence on the soil load acting on the buried pipes. However, Moser and Folkman (1990) did not investigate how the soil arching changed with respect to the soil cover thickness and distance from the pipes.

The classical Marston load theory, proposed by Marston and Anderson (1913), calculates vertical soil load transferred to the top of flexible pipes using trench and embankment equations. At present, a number of methods for predicting the soil load on the top of buried pipes have been proposed (Spangler 1948; Zeng 1960; Matyas and Davis 1983; Lou and Wang 2003; Li and Zhang 2008). However, most of the above calculation methods are derived from researches on rigid buried pipes such as concrete pipes, and have not considered the installation effect. In Chinese practice, the China Engineering Construction Standard (CECS 2004) simply assumes that the earth pressure on the top of a HDPE pipe is equal to the geostatic stress of the overburden soil, ignoring the soil arching effect.

As a result, the purposes of this study are to (1) conduct full-scale field tests to measure earth pressures at the top and springline of shallowly buried HDPE pipes in the construction phase; (2) investigate the change of the soil arching with regard to the soil cover thickness; and (3) compare the field measured earth pressures on the top of HDPE pipes with those predicted by the Marston load theory.

2. TESTING METHODOLOGY

2.1 Testing pipes and instrumentation

Three double-wall corrugated HDPE pipes labeled as P1, P2 and P3 were used in the field tests, and the properties of the pipes are shown in Table 1.

Table 1 Properties of the HDPE pipes

Pipe ID	Nominal diameter (mm)	Laminated wall thickness (mm)	Corrugation depth (cm)	Corrugation length (cm)	Ring stiffness* (kPa)
P1	600	2.7	4.5	9	4
P2	600	2.7	4.5	9	4
P3	300	3.4	1.9	4	4

Note: *ring stiffness = EI/D_o^3, where E = modulus of elasticity of the pipe material (kPa), I = moment of inertia of the pipe (mm^3), and D_o = mean diameter of the pipe (mm).

During the pipe installation, the earth pressure cells were used to monitor the earth pressures. The earth pressure cell was vibrating wire-type, with diameter of 25 mm. The measurement range of pressure cell varied from 0 to 0.5 MPa, and its accuracy and resolution were 0.5% Full Scale (FS) and 0.01% FS, respectively. The arrangement of earth pressure cells is shown in Figure 1. For the 600-mm diameter pipes, the earth pressure cells were positioned at the springline and top of the pipes, and above the pipes at varying soil depths. For the 300-mm diameter pipe, two earth pressure cells were installed at the top of the pipe and a height of 300 mm above the top of the pipe, respectively. All the pressure cells were calibrated prior to the installation. A data acquisition system (dataTaker 80) was used to record the measured soil pressures.

In addition to the earth pressures, strain and deflections of the pipe were also monitored using strain gauges and dial-gages, respectively, during the construction phase. The details of the configuration of the strain gauges and dial-gauges and measured results can be found in You et al. (2014).

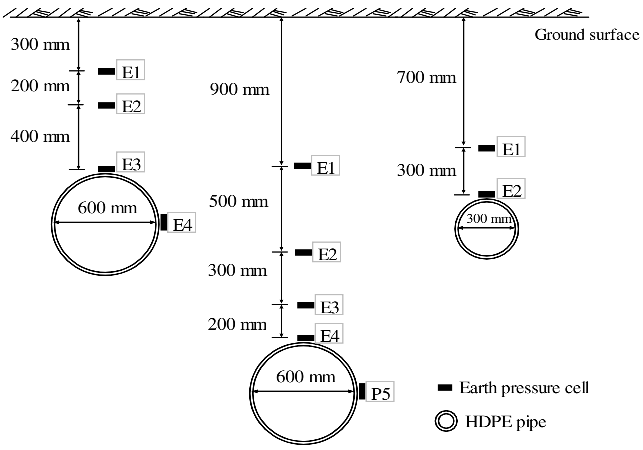

Figure 1 Arrangement of earth pressure cells in field tests

2.2 Site conditions

The field test is located in the Xinzhuang bridge construction site, Yixing City of China. The properties of the ground soil are shown in Table 2. The grain size distribution curve of the sand used as the bedding and base of the pipe is shown in Figure 2. Based on the Unified Soil Classification System (ASTM D2487), the ground soil is classified as lean clay (CL) and the sand is classified as well-graded (SW).

Table 2 Properties of the ground soil

Water content (%)	Liquid limit (%)	Plastic limit (%)	Density (kg/m^3)	Void ratio	Maximum dry density* (kg/m^3)
18	38	17	2.02×10^3	0.59	1.8×10^3

Note: *Maximum dry density is obtained from the modified proctor compaction test as per ASTM D1557.

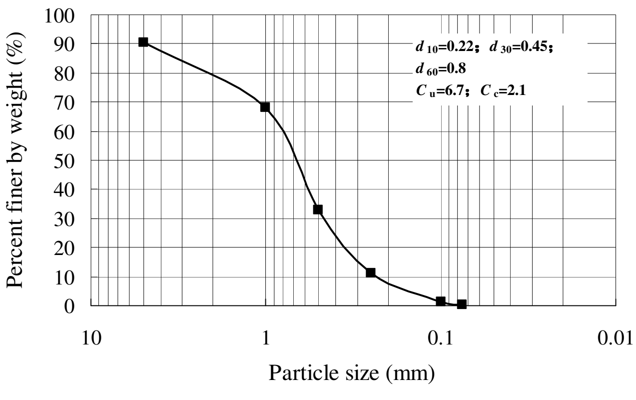

Figure 2 The grain size distribution curve of the sand

2.3 Testing methods

Three trenches with cross-section dimension of 2 m in width and 3 m in length were excavated to 1.4 m, 1.6 m and 2.6 m depths, respectively. Before backfilling the excavated ground soil, the air-dried sand was filled and compacted to a 100 mm–thickness-lift serving as the bedding of the pipe. After the instrumentation of earth pressure cells and data Taker in the pipe, the sand was filled and compacted to a 150 mm-thickness lift serving as the haunch of the pipe. Then the excavated ground soil was backfilled around the HDPE pipe up to the height of 0.5 m over the top of the pipe, and was tamped by hand tamping at every compacted lift with a thickness of 0.2 m. After that, the ground soil was backfilled up to the designed filling height and was tamped by mechanical tamping at every compacted lift with a thickness of 0.1 to 0.2 m. The compaction degrees of the backfills outlined by the CECS (2004) are shown in Figure 3.

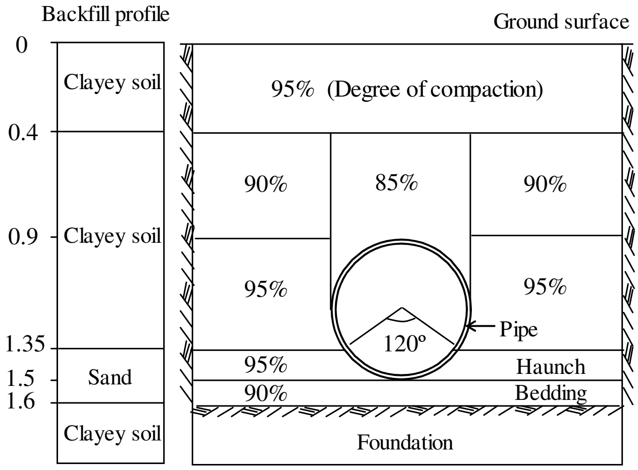

Figure 3 Compaction degree of the backfilled soil in the trench

3. RESULTS AND DISCUSSION

3.1 Measured earth pressures

Figure 4 presents the variation in the measured earth pressure with the soil cover thickness. The earth pressure at the springline of the pipe is larger than the earth pressure on the top of the pipe. The observation is attributed to the occurrence of vertical compressive (i.e., inward) deflection of the pipe induced by the overburden earth pressure, which in turn results in positive soil arching above the pipe and a subsequent transfer of the earth pressure at the top of the pipe to the lateral soil around the pipe.

3.2 Development of soil arching

The soil arching ratio (k) is defined by the following equation (McNulty 1965):

$$k = P / \gamma h \tag{1}$$

where P = earth pressure acting on the pipe crown (kPa), γ = average unit weight of the backfill over the pipe (kN/m^3), and h = soil cover thickness (m).

Figure 5 presents the variation in the soil arching ratio with the soil cover thickness. All of the values of k are less than 1.0, indicating that positive soil arching is exerted in the soil around the pipes. Above the pipe, k decreases with increasing soil cover thickness while it increases with increasing soil cover thickness at the pipe sprigline, irrespective of the pipe diameter. For instance, at the top of the P1 pipe (E3), the values of k at the soil cover thicknesses of 1.5 m (k = 0.82) is 0.1 unit less than that at the soil cover thickness of 1.0 m (k = 0.92). For the soil arching ratio at the springline of the P1 pipe (E4), its value is 0.8 at the soil cover thickness of 0.9 m and is 4.7 times greater than that at the soil cover thickness of zero.

The change of soil arching ratio with the soil cover thickness is attributed to the positive soil arching developed above the pipes, which transfers a portion of crown pressure to the soil backfilled around the pipe. With more significant positive soil arching, greater portion of crown pressure is shifted to the surrounding soil. Higher soil cover thickness yields larger vertical deflection of the pipes and greater degree of mobilized positive arching as a consequence. The soil arching ratio at the pipe crown decreases with increasing soil cover thickness, while it exhibits opposite pattern at the pipe springline.

It can be seen from Figure 5(a) that when the construction of P1 pipe is completed, the soil arching ratio (k = 0.82) on the top of the pipe (E3), is 6% and 12% less than those at the elevations of 0.4 (E2) and 0.6 m (E1) above the P1 pipe, respectively. Similar observations are also found for the P2 and P3 pipes as shown in Figure 5(b and c). Although the settlements of the backfill above the pipe were not monitored in this study, the authors believe that the phenomena are attributed to the occurrence of greater settlement at the position closer to the pipe crown, which results in more notable positive soil arching developed in the backfill.

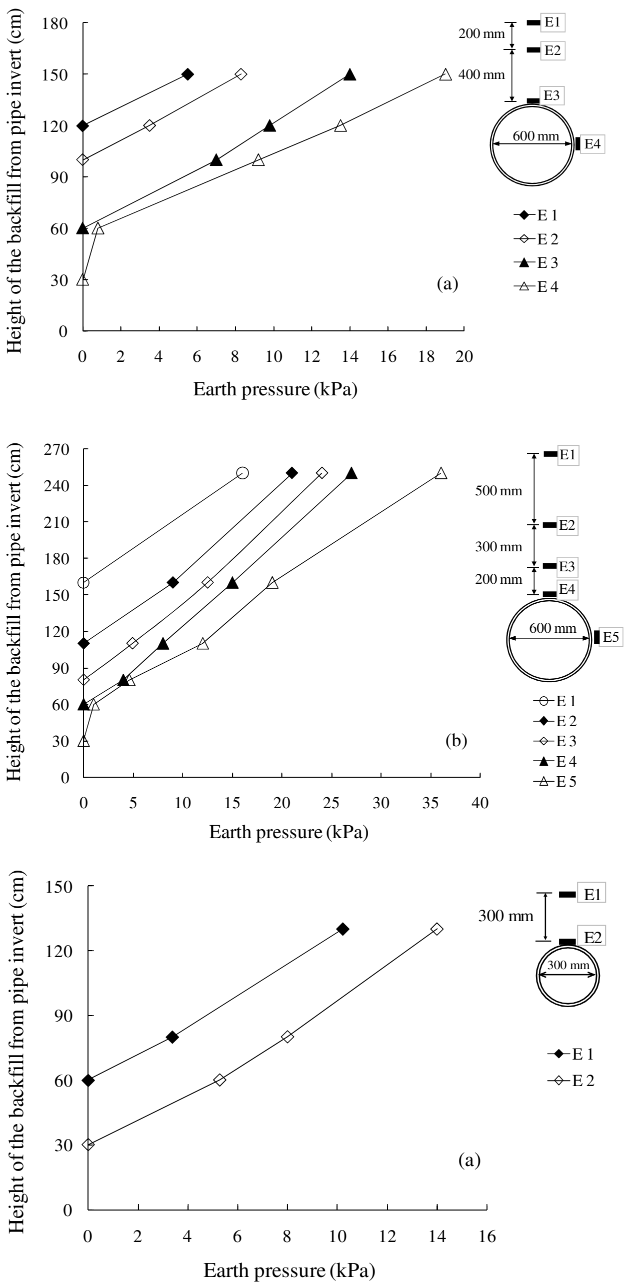

Figure 4 Variation in the measured soil pressure with height of the backfill from the pipe invert: (a) P1 pipe, (b) P2 pipe and (c) P3 pipe

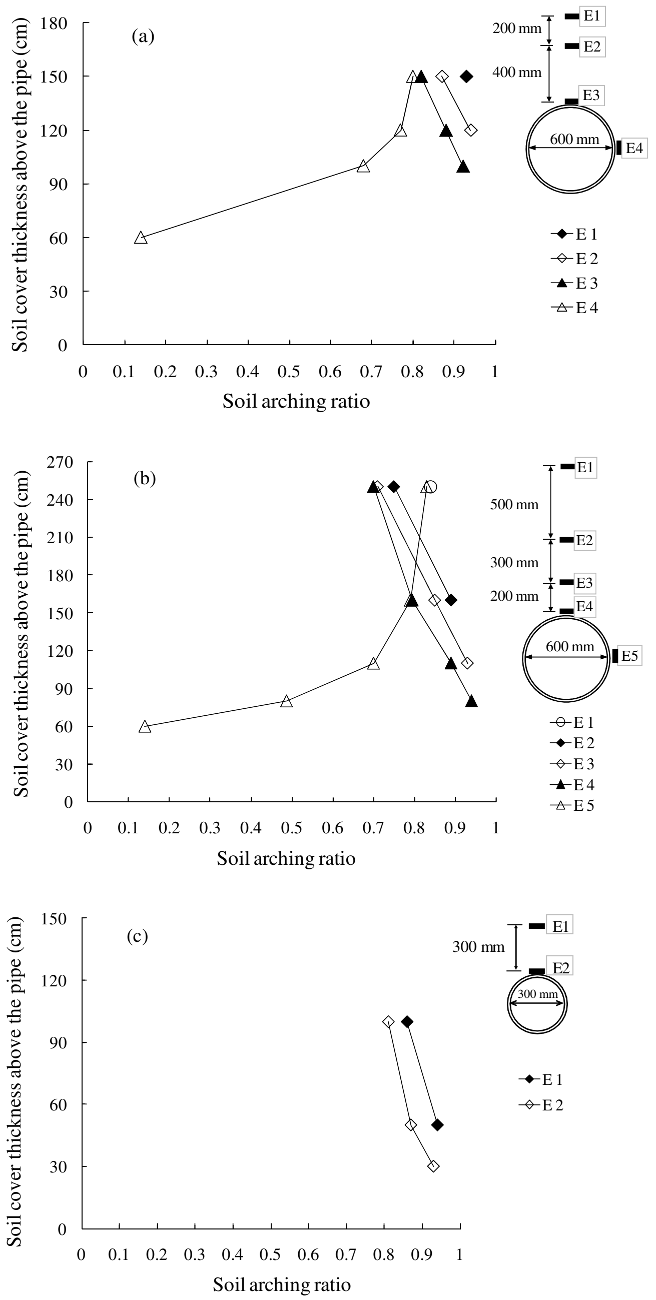

Figure 5 Variation in the soil arching ratio with soil cover thickness above: (a) P1 pipe, (b) P2 pipe and (c) P3 pipe

3.3 Earth pressure predicted by the Marston load theory

Based on the Marston load theory, the vertical soil load acting on a unit length of the flexible pipe buried in the trench is expressed by (Moser and Folkman 1990):

$$W_d = C_d \gamma B_c B_d = (1 - e^{-2K\mu(H/B_d)})\gamma B_c B_d / 2K\mu \qquad (2)$$

where W_d = soil load on a unit length of the pipe (kN/m), γ = unit weight of the soil cover (kN/m^3), B_c =outside diameter of the pipe (m), B_d = trench width (m), K = ratio of horizontal stress at the wall to average vertical stress, μ = coefficient of sliding friction between the soil and the trench wall, and H = soil cover thickness above the pipe (m). For the flexible pipes buried in the embankment, the soil load on a unit length of the pipe is calculated by the Marston's embankment equation as following (Moser and Folkman 1990):

$$W_c = C_c \gamma B_c^2 \tag{3}$$

$$C_c = ((e^{\pm 2K\mu(H_e/B_c)} - 1)/\pm 2K\mu) + (H/B_c - H_e/B_c)e^{\pm 2K\mu(H_e/B_c)} \tag{4}$$

where W_c= soil load on a unit length of the pipe (kN/m), μ = internal friction coefficient of backfill, H_e = the height of the plane of equal settlement, and other parameters are defined in Eq. (2).

The earth pressure (P, kPa) acting on the top of the HDPE pipe is therefore calculated by dividing the soil load (W_c) by the outside diameter of the pipe (B_c) using the following two equations for the trench condition and embankment condition, respectively:

$$P = W_d / B_c = C_d \gamma B_d = (1 - e^{-2K\mu(H/B_d)})\gamma B_d / 2K\mu \tag{5}$$

$$P = W_c / B_c = C_c \gamma B_c = (1 - e^{-2K\mu(H/B_c)})\gamma B_c / 2K\mu \tag{6}$$

The above two equations (Eqs. (5) and (6)) simply assume that the vertical soil load on the pipe distributes uniformly along the pipe circumference. Particularly, H_e in Eq. (4) is assumed to be equal to soil cover thickness H in Eq. (6), as the positive soil arching exerted in the soil cover above the pipes is not stabilized until the soil cover thicknesses above the P1, P2 and P3 pipes reach 0.9 m, 1.9 m and 1 m, respectively (see Figure 5). It is worth to note that a threshold trench width (B_d) exists in using Marston load theory for estimating soil load on the rigid pipes buried in the trench. When the trench width is smaller than the threshold value, the Marston's trench equation is suggested; or if not, the embankment equation should be used (Moser and Folkman 1990). However, for the flexible pipe (e.g. the HDPE pipe), relevant researches are non-exist. In this study, the computed earth pressures at the top of the pipe using Eqs. (5) and (6) are compared with the field measured data to figure out the existence of threshold B_d. The values of parameters used in Eqs. (5) and (6) are listed in Table 3. Particularly, the values of $K\mu$ were set as 0.13 and 0.19, as recommended by Moser and Folkman (1990), for Eqs. (5) and (6), respectively. For the Marston's trench equation, the settlement ratio is arbitrarily assumed as -0.2 for the purpose of estimating the value of C_c since positive soil arching occurs above the HDPE pipes in this study (Moser and Folkman 1990). Preliminary study shows that the settlement ratio at a range of -0.2 to -0.1 results in marginal difference in estimation of earth pressure at the top of the pipe using Eq. (6).

Table 3 Parameters used for estimating earth pressures on the top of the pipe using the Marston load theory

Parameter	Value		
	P1 pipe	P2 pipe	P3 pipe
B_c (m)	0.693	0.693	0.341
B_d (m)	2.0	2.0	2.0
H* (mm)	0, 400, 600 and 900	0, 200, 500, 1000 and 1900	0, 300, 500 and 1000
γ (kN/m^3)	0, 19.5, 19.6 and 19.81	0, 19.5, 19.5, 19.85 and 20.01	0, 19.5, 19.5 and 19.85
$K\mu$	0.13 (Eq. (5)) 0.19 (Eq. (6))	0.13 (Eq. (5)) 0.19 (Eq. (6))	0.13 (Eq. (5)) 0.19 (Eq. (6))
C_d	0, 0.19, 0.28 and 0.42	0, 0.1, 0.24, 0.46 and 0.83	0, 0.15, 0.24 and 0.46
C_c**	0, 0.53, 0.8 and 1.1	0, 0.29,0.7, 1.24 and 2.14	0, 0.85, 1.4 and 2.3

Note: * From the top of the pipe; ** Settlement ratio was -0.2 for the estimation of C_c.

Figure 6 presents the comparison of the earth pressures at the top of the pipe measured in the field tests with those calculated by Eqs. (5) and (6). It can be seen that the predicted values using the stationary prism load (i.e., geostatic stress) result in higher crown pressures relative to the measured ones or predicted ones using the Marston's trench and embankment equations, which is more noticeable when the soil cover thickness increases. The Marston's embankment equation (Eq. (6)) yields a better prediction as the predicted earth pressures are closer to the field measured ones, irrespective of the pipe diameter, soil cover thickness or position of the pressure cell. The earth pressure at the top of the P1, P2 and P3 pipes calculated by the Marston's trench equation (Eq. (5)) are 8% to 20%, 7% to 25% and 8% to 32% higher than the measured ones in the field tests, respectively; the earth pressures calculated by the Marston's embankment equation (Eq. (6)) are 2% to 11%, 8% to 14% and 7% to 12% greater than the measured ones, respectively. The phenomenon suggests that for the HDPE pipes shallowly buried in the 2-m-width trench, a threshold trench width is very likely to exist for choosing proper equation for calculating the earth pressure or soil load on a unit length of the pipe, at least for this study. Further study needs to be conducted to investigate the value of this threshold trench width.

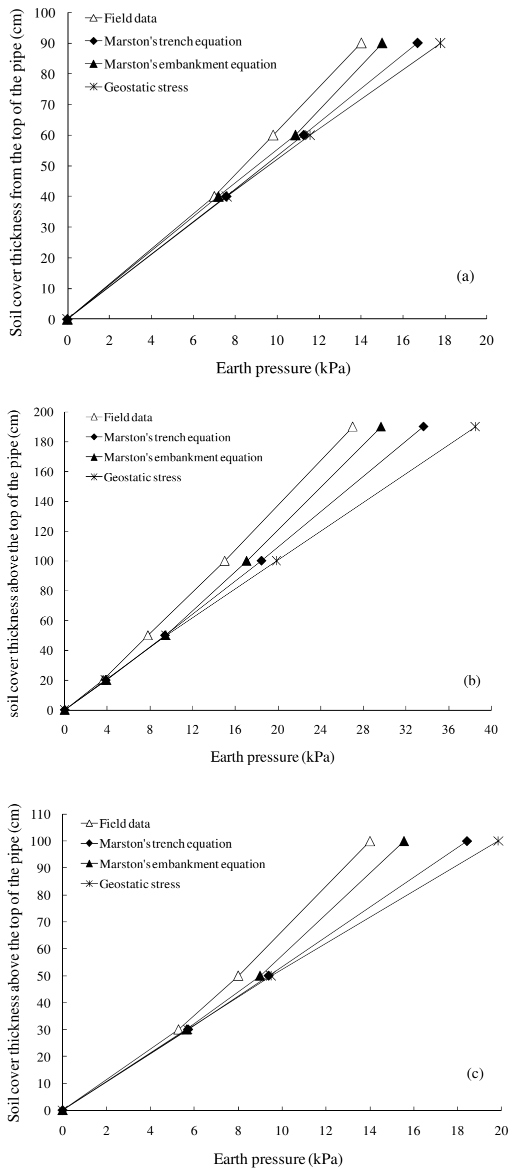

Figure 6 Comparisons of earth pressures acting on the top of the pipe between those measured in the field tests and calculated using the Marston load theory: (a) P1 pipe, (b) P2 pipe and (c) P3 pipe

4. CONCLUSIONS

Field tests were conducted for 0.3-m-diameter and 0.6-m-diameter HDPE pipes buried in the trench with width of 2 m and length of 3 m. The test section was instrumented to monitor the earth pressures at the springline and top and above of the pipe during the construction phase. The change of soil arching with regard to the height of the backfill from the pipe invert was investigated. The earth pressures at the top of the pipe measured in the field tests were compared with those estimated by the Marston load theory. The following conclusions can be drawn:

(1) The measured earth pressure at the top of the pipe is lower than that at the pipe springline, and it is attributable to the positive soil arching above the pipe.

(2) When the construction phases of HDPE pipes are completed, soil arching ratios on the top of the P1, P2 and P3 pipes are 11%, 25% and 23% lower than their corresponding initial values, respectively. The soil arching ratios at the springline of the P1 and P2 pipes are almost 4.7 and 5.4 times greater than the initial values, respectively. The results demonstrate that soil arching developed above the pipes becomes significant with the increase in the soil cover thickness, implying that earth pressures at the springline and top of the HDPE pipe could be predicted effectively from the perspective of development of soil arching triggered in the backfill around the pipe.

(3) At a given soil cover thickness, the soil arching was more notable at the position closer to the top of the pipe, which may be attributed to the greater settlement and needs to be investigated in the further studies.

(4) The Marston's embankment equation resulted in closer prediction of the earth pressure at the top of the pipe to the measured values relative to the Marston's trench equation. The earth pressures calculated by the Marston's trench equation and embankment equation were 8% to 32% and 2% to 14% greater than those measured in the field tests, respectively. The results suggested that a threshold trench is likely to exist when Marston load theory is used for calculating the earth pressure at the top of the pipe. Further studies need to be conducted on the threshold trench width.

5. ACKNOWLEDGEMENTS

This research is financially supported by the National Natural Science Foundation of China (Grant No. 51278100 and 51108078) and Natural Science Foundation of Jiangsu Province (Grant No. BK20131294 and BK2012022).

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