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Laboratory evaluation of buried high-density polyethylene pipes subjected to localized ground subsidence

Abstract

The serviceability loss of buried high-density polyethylene (HDPE) double-wall corrugated pipes caused by localized ground subsidence has been reported all over the world. Beam-on-nonlinear spring model is widely used to analyze the structural responses of buried pipes to the localized ground subsidence underneath the pipe. However, the pipe-soil separation is not considered by the beam-on-nonlinear spring model which assumes bonded interaction between the pipe and soil. This is because the spring stiffness could not be assigned as zero. The bonded interaction between pipe and soil is not able to capture the pipe behavior and characteristics of load distribution around the pipe when pipe-soil separation occurs. This study presents a series of large-scale model tests aiming to investigate the performance of buried HDPE double-wall corrugated pipes subjected to the localized ground subsidence. Movable plates installed at the bottom of the model test box are lowered down to simulate the localized ground subsidence. Earth pressures, pipe vertical displacements, and settlements at the backfill surface are monitored. For comparison purpose, free field condition (i.e., without pipe) is also tested. The test results demonstrate that soil settlement troughs above buried pipes are shallower and wider than those at the same elevation in the free field condition. Earth pressures at the top of the pipe are found to increase due to the negative soil arching, i.e., earth pressure is greater than the overburden pressure. It is suggested that three-dimensional soil arching, i.e., soil arching effects in both the transverse and longitudinal directions of the tested pipe, should be considered in calculating the earth pressures at the pipe top. The pipe-soil separation is substantiated by the observation that earth pressure measured at the bottom of the pipe is zero. Finally, empirical equations are proposed to correlate the volume of pipe displacement profile with the volume of settlement trough at the backfill surface to facilitate evaluation of the performance of the pipes subjected to the localized land subsidence.

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**Laboratory Evaluation of Buried High Density Polyethylene Pipes Subjected to Localized
Ground Subsidence**

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Abstract: The serviceability loss of High Density PolyEthylene (HDPE) double-wall corrugated pipes caused by localized ground subsidence has been reported all over the world. Theory of beams on Winkler elastic foundation is commonly used to analyze structural responses of buried pipes subjected to ground subsidence. However, the theory of beams on Winkler elastic foundation assumes that the displacement of buried pipes exactly matches the soil settlement trough (i.e., the displacement of pipe is equal to the soil settlement underneath the pipe). This assumption is not able to present the pipe behavior and load distribution around the pipe when pipe-soil separation occurs at the pipe-soil interface by which the pipe response (i.e., internal stresses and strains) would be overestimated. A series of large-scale model tests are carried out to investigate the performance of HDPE double-wall corrugated pipes subjected to localized ground subsidence. Movable plates installed at the bottom of the box are lowered down to simulate localized ground subsidence. Earth pressures, pipe vertical displacements, and surface settlements of the backfill are measured. For comparative studies, free field soil (i.e., without pipe) is also tested. The test results demonstrate that soil settlement troughs for buried pipes have shallower but wider shapes than those of the free field soil. The vertical displacements of the pipe are smaller than those in the free field soil. Based on the observation that the earth pressures at the top of the pipe increase because of negative soil arching (i.e., earth pressure is greater than overburden pressure) at the top of the pipe, it is suggested that three-dimensional soil arching effect should be considered in accurately modeling the earth pressures at the pipe top. It is also observed that the earth pressures at the bottom of pipes have been reduced to zero during the forming of the ground subsidence, which confirms the occurrence of the pipe-soil separation. The widely used theory of beams on Winkler elastic foundation in buried pipe design, assuming no separation between soil and pipe, will induce errors for buried pipes subjected to ground

54 subsidence. Finally, empirical equations are proposed to correlate the volume of pipe displacement
55 profile with the volume of settlement trough at the backfill surface to facilitate the estimation of pipe
56 performance in practice.

57 **Key words:** large-scale physical model test; Localized ground subsidence; HDPE pipe;
58 Three-dimensional soil arching.

59 **1 Introduction**

60 High density polyethylene (HDPE) double-wall corrugated pipes have been widely used in
61 engineering practice due to its high corrosion resistance and low cost. It is reported that in length
62 HDPE double-wall corrugated pipes make up of more than 50% of all urban drainage pipelines in
63 China (Wu 2014). It is found that some buried HDPE pipes are affected by localized ground
64 subsidence occurred in many cities due to groundwater pumping (Shen and Xu 2011; Xu et al., 2012,
65 2016) or urban construction (Han et al. 2015; Shen et al, 2016; Wu et al., 2016). For examples, sewer
66 pipelines are damaged by tunneling-induced ground subsidence in Zhengzhou, China (Zhou 2009).
67 Nine people are injured with a massive traffic jam. The ground subsidence induced by irregular
68 underground construction causes the destruction of water-supply HDPE pipelines in Shanghai China
69 (Luo 2015). Three types of additional stresses may act on pipes during localized ground subsidence
70 (e.g., Liu and O'Rourke 1997; Vorster 2005; Gantes and Bouckovalas 2013; Han et al. 2013; Shen et
71 al. 2014; Kouretzis et al. 2015): (1) flexural stress caused by the loss of support at the pipe invert
72 level. Consequently earth pressure at the top of the pipe is elevated due to negative soil arching (i.e.,
73 load on pipe is greater than the overburden stress); (2) shear stress at the pipe-soil interface in the
74 pipe longitudinal direction due to slippage at the pipe-soil interface; and (3) tensile stress due to the

axial elongation of the HDPE pipes. However, in the existing methods the performance of pipes associated with localized ground subsidence is not well considered.

Buried pipes subjected to the ground subsidence are normally analyzed using the beams on Winkler elastic foundation model, in which the pipe is represented as a beam-type structural element surrounded by a series of independent nonlinear soil springs (ASCE 1984; ALA 2001; Shen et al. 2014). The value of soil spring stiffness depends on the pipe-soil relative displacement and properties of the soil medium, i.e., internal friction angle, cohesion, and unit weight (Yin et al., 2011, 2017; Yin and Chang, 2013). However, it is difficult to estimate pipe-soil relative displacement because the effect of a pipe on ground subsidence propagation has not been well explored. In addition, phenomenon of pipe-soil separation has been reported in some previous studies (e.g., Vorster 2005; Vorster et al. 2005; Wang et al. 2015). It is observed that the bending behavior of the pipe with ground subsidence is affected significantly by the pipe-soil separation. However, the pipe-soil separation cannot be simulated by the beams on Winkler elastic foundation model because the spring stiffness cannot be set to zero. Consequently additional stress and strain caused by localized ground subsidence will be overestimated. A curve-fitting technique for predicting pipe deformation with the ground subsidence is extensively employed (e.g., Newmark and Hall 1975; Kennedy et al. 1977; Wang and Yeh 1985; O'Rourke 1989; Karamitros et al. 2007; Trifonov and Cherniy 2012; Karamitros et al. 2011, Newmark and Hall, 1975). In the method, the effect of pipe bending stiffness on the pipe deformation is neglected and the buried pipe deforms as a catenary shape under the strike-slip fault. Wang and Yeh (1985) approximate the deformed pipe segment crossing the fault zone by a circular arc, and the deflection at far ends of buried pipes fitted by using trigonometric functions. O'Rourke (1989) employs the cosine function and fixed-fixed beam model to calculate the

deformation of flexible and rigid pipes, respectively. However, the calculation procedures are too complicated in terms of many site-specific parameters for practical application.

The pipe-soil interaction under the ground movement condition has been investigated using different testing approaches, such as field tests, centrifuge model tests and large-scale model tests. Chan and Wong (2004) report a field case study on the steel pipe responses to landslides. They find that the transverse soil movement has more significant effect on the structural behaviors of the pipes than the longitudinal one. Li et al. (2012) investigate the influence of faulting offset and pipe dimensions on behaviors of buried HDPE pipe subjected to faulting through laboratory model tests. Their results show that the pipe with larger flexural stiffness has smaller bending strains. Centrifuge tests are another effective tool to investigate the pipe responses to the ground subsidence (e.g., O'Rourke et al. 2005; Vorster 2005; Bransby et al. 2007; Choo et al. 2007; Ha et al. 2008; White et al. 2008; Daiyan et al. 2011; Saiyar 2011 and Saiyar et al. 2016). O'Rourke et al. (2005) report that the pipe strains measured from the tests are compared with those from finite element (FE) modeling, and it is seen that the centrifuge technology is capable of reproducing the pipe responses subjected to the strike-slip fault. Vorster (2005) conducts a series of centrifuge modeling tests with 75 g acceleration to investigate the pipe responses to the tunneling-induced ground subsidence. Three types of model pipes, i.e., two aluminum alloy pipes and one acrylic pipe, with radius/thickness ratios of 21, 12, and 7 are used. Saiyar (2011) performs centrifuge tests with 30 g acceleration to investigate the pipe-soil interaction for pipes crossing normal faults. Solid rods with a length of 0.8 m and a diameter of 9.5 mm are fabricated to generate equivalent bending stiffness with the prototype pipes. Because the wall thickness of the profiled wall pipes is only several millimeters (e.g., double-wall corrugated HDPE pipes with liner thickness of less than 5 mm), it is very difficult to produce centrifuge modelling

~~pipes~~ with appropriate pipe sizes.

Large-scale model tests are widely used for a reliable database characterizing ground subsidence-induced pipe responses (e.g., Trautmann and O'Rourke 1983; Yoshizaki et al. 2003; Anderson et al. 2005; Weerasekara and Wijewickreme 2008; O'Rourke et al. 2010; Almahakeri et al. 2012; Yang et al. 2012; Wang et al. 2015). Trautmann and O'Rourke (1983) conduct laboratory model tests to investigate the response of steel pipes with diameters of 102 and 324 mm subjected to ground movements associated with earthquakes. They find that the relationship between earth pressure and displacement of the pipe can be represented by bilinear or hyperbolic functions. Almahakeri et al. (2012) investigate the responses of 115-mm-diameter and 1830-mm-long glass fiber reinforced polymers pipes buried in dense sand subjected to the ground movement. They report that the peak earth pressure acting on the pipe increases with the burial depth. It is recognized that the earth pressure acting on the pipe is essential for estimating additional stress and deformation of the pipe with ground subsidence (Jiang and Yin, 2012, 2014). However, very limited studies are found in the literature about the earth pressure acting on the flexible pipes subjected to the ground subsidence.

In addition, pipelines are buried in the ground and thus the displacement and internal forces are difficult to measure in practice. Therefore, an alternative way by using the ground surface settlement trough to predict the additional displacement and internal force of pipes is valuable (e.g., Duan 2002; Wang et al. 2015; Ni 2016). Duan (2002) proposes a method to predict the deformation of pipes subjected to tunneling based on the volume loss of ground surface. Wang et al. (2015) investigate the ground responses to tunneling considering the existence of HDPE double-wall corrugated pipes. The moveable bottom plates of the model box are lowered to form normal distribution curves for

141 simulating the ground movement induced by tunneling. They find that the existence of HDPE pipes
142 induces a wider but shallower soil settlement trough as compared to the free field (i.e., no pipe). Ni
143 (2016) establishes a design framework to calculate the bending strain of buried pipes subjected to the
144 normal fault based on the estimation of trough width parameter at the ground surface (i.e., the
145 distance from the point of inflection to the peak curvature point). Nevertheless, the response of
146 HDPE pipe to localized ground subsidence (i.e., an area with deep and narrow depression) has not
147 been well understood. The localized ground subsidence can be caused by soil pumping, karst
148 evolution, ground collapse due to pipe leak, and so on.

149 In this study, a series of large-scale model tests are conducted to investigate the structural
150 responses of HDPE double-wall corrugated pipes subjected to localized ground subsidence. The
151 movable plates installed at the bottom of the model box are lowered down in designed sequences to
152 simulate the progressive development of the ground subsidence. Earth pressures, vertical
153 displacements of the pipe, and settlements at different depth are monitored during the tests. The
154 effects of bending stiffness and burial depth of the pipe on its structural responses are investigated. A
155 correlation of pipe displacement and the settlement trough at the ground surface is developed. The
156 result of this study is useful for understanding both qualitatively and quantitatively the performance
157 of buried flexible pipes subjected to localized ground subsidence.

158

159 **2 Testing Instrumentation and Measurements**

160 ***2.1 Testing pipes and backfilling materials***

161 Four HDPE double-wall corrugated pipes (labeled as P1, P2, P3 and P4) with inner diameters of
162 200, 300 and 400 mm and a length of 2 m are adopted in the model tests. Physical properties of the

163 pipes are tabulated in **Table 1**. Yangtze River sand is used as the backfill material. The sand is first
164 air dried and passed through a sieve with an opening size of 2 mm to exclude large particles. The
165 specific gravity, measured in accordance with [ASTM D854 \(ASTM 2014\)](#), is 2.65, and the minimum
166 and maximum densities, measured in accordance with [ASTM D4253 \(ASTM 2014\)](#), are 1.39 and
167 1.51 Mg/m³, respectively. The gradation characteristics of the sand are listed in **Table 2**. Based on
168 the Unified Soil Classification System, [ASTM D2487 \(ASTM 2011\)](#), the sand is classified as poorly
169 graded sand (SP).

170 **Table 1** Physical properties of the HDPE pipes

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Pipe ID	Inner pipe diameter (mm)	Inner wall thickness (mm)	Laminated wall thickness (mm)	Depth of corrugation (mm)	Pitch of Corrugation (mm)
P1	200	1.2	1.7	10	30
P2	300	1.7	2.2	15	40
P3	300	1.7	2.2	15	40
P4	400	2	2.5	25	50

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Table 2 Gradation characteristics of Yangtze River sand

Parameters	Value
Particle size fraction	
Medium sand (0.425- 2 mm) (%)	27.44
Fine sand (75 - 425 μm) (%)	72.56
D_{60} (mm)	0.40
D_{30} (mm)	0.23
D_{10} (mm)	0.14
Uniformity coefficient C_u	2.86
Curvature coefficient C_c	0.94

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176 **2.2 Test apparatus**

177 The physical model box is 2.0 m in width, 2.0 m in length and 1.5 m in height, as shown in **Fig.**

1. The side walls of the box except for the front one are made of 15-mm-thick polyethylene sheets and stiffened by steel frames to minimize side deflections. The front wall is made of Plexiglas plate with a thickness of 12 mm, allowing visual observation of soil movements. The bottom of the box is made up of eight movable plates, and each plate is 0.10 m thick, 0.25 m wide and 2 m long. Lowering devices are used to control the vertical movement of the bottom plates by manually rotational handles beneath the model box, and each individual lowering device connects to a single movable bottom plate. The maximum lowering distance of the bottom plates is 100 mm, and ten rounds of handle results in 1 mm displacement. Details of the instrumentations can be found in Wang et al. (2015). Two fixing frames are designed to connect the ends of HDPE pipes with the wall of the model box where no occurrence of pipe-soil slippage occurs. A pipe plug mounted on the fixing frame could be pushed into the pipe end to simulate a spigot joint, and a 1.5-mm-thick rubber gasket is also installed between the plug and test pipe to tighten the connection.

Fig. 1 Schematic of the model box (unit: mm) (modified from Wang et al., 2015)

To ensure uniformity of the backfill, the sand is backfilled in the model box using a

195 custom-made sand pluviation device. The sand is first lifted up to the pluviation device by a belt
 196 conveyor, and then falls into the model box from a sieve with an opening size of 2 mm installed at
 197 the bottom of the pluviation device to exclude large particles and to eliminate the velocity effect of
 198 sand particles on the backfill density. In order to keep the falling height of the sand consistent, the
 199 pluviation device is moved upward by 0.1 m after a 0.1-m-thick sand layer is backfilled into the box.
 200 Prior to filling, the relationship between the falling height and density of the sand is obtained by
 201 conducting a pluviation test, as shown in **Fig. 2** (Wang et al. 2015). The falling height of the sand
 202 adopted in the tests is 0.7 m, and the corresponding sand density is 1.46 Mg/m³. The state of
 203 compactness of the sand is defined as medium dense with a relative density of 62% and constrained
 204 modulus is estimated as 3.52 MPa under overburden stress of 12.5 kPa (similar with the overburden
 205 stress at the level of pipe axis, i.e., 13.1 kPa for the P1, P2 and P4 pipes and 8.8 kPa for the P3 pipe)
 206 using the method suggested by [ASTM D2435M](#) (ASTM 2011). The internal friction angle of the
 207 sand with density of 1.46 Mg/m³ is determined as 32.5° by direct shear tests as per [ASTM D3080](#)
 208 ([ASTM 2011](#)).

210

Fig. 2 Relationship between the falling height and dry density of the sand

Custom-made settlement plates and dial gauges are used to monitor the vertical displacement of the pipe and the settlement at different depth. Schematic diagram of the settlement plate is shown in **Fig. 3** (Wang et al. 2015). Two square plates with side length of 50 mm and thickness of 5 mm are fixed on the ends of 10-mm-diameter rods, and the rods are enclosed in PVC tube to eliminate the friction between settlement plate and sand. In order to reduce the effects of self-weight of the settlement plates on the settlement measurement, the square plates and rods are made of lightweight plexiglass. The dial gauge used in this study has a range of 0 to 50 mm and an accuracy of 0.1 mm.

Fig. 3 Settlement plate (unit: mm; “y” depends on the distance from the monitoring point to the backfill surface)

Earth pressure cells with the range of 0 to 0.2 MPa are used in the model tests, and its accuracy and resolution are 0.5% Full Scale (FS) and 0.01% FS, respectively. A data acquisition system is connected with the earth pressure cells to record data at a time interval of two seconds automatically. Earth pressure cells are calibrated prior to the tests and compared with the calibration factors from the manufacturers to ensure the accuracy of the test results.

230

231 **2.3 Test methods**

232 P1, P2 and P4 pipes have a burial depth of 0.9 m (i.e., the distance from the axis of the pipe to
 233 the backfill surface), while the burial depth of P3 pipe is 0.6 m. Settlement propagation is also
 234 observed in the free field (i.e., no pipe) condition. The details of all test cases are shown in **Table 3**.
 235 Three measuring sections are setup to capture the earth pressure and settlement distribution of the
 236 soil and pipe. Section 1 is located at a horizontal distance of 500 mm from the centerline of the pipe,
 237 Section 2 is located at the center of the pipe, and Section 3 is 250 mm from the centerline, as shown
 238 in **Fig. 4**. Earth pressure cells are installed at the pipe top at Sections 1 and 2. For the P4 pipe, the
 239 earth pressure cells are also installed at the bottom of the pipe at Sections 1 and 2 to record the
 240 potential pipe-soil separation with the development of the subsidence simulated by lowering of
 241 bottom moveable plates. Settlement plates are placed at the pipe top at Sections 1, 2 and 3 to measure
 242 the vertical displacement of the pipe. The settlement at the backfill surface is measured by placing
 243 the foot of dial gauge on a lightweight plexiglass square plate with a side of 50 mm placed on the
 244 backfill surface. In the free field case, the settlement plates are placed at the depths of 0, 0.3, 0.6 and
 245 0.9 m, respectively, as shown in **Fig. 4(e)**.

246

247 **Table 3** Summary of test cases

Cases	Pipe ID	A (m ² /m)	EA (kN/m)	EI (kNm ²)	Pipe stiffness (kPa)	Inside pipe diameter (mm)	Burial depth ^a (m)
1	P1	0.0044	2000	5	215	200	0.9
2	P2	0.0067	3000	18	215	300	0.9
3	P3	0.0067	3000	18	215	300	0.6
4	P4	0.0078	3500	48	215	400	0.9

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Fig. 4 Testing instrumentation: (a) P1 pipe; (b) P2 pipe, (c) P3 pipe, (d) P4 pipe and (e) free field (no pipe) (unit: mm)

The range and magnitude of localized ground subsidence are simulated by lowering down the bottom plates in a designed sequence (labeled as #3, #4, #5 and #6 in **Fig. 1**). Moving patterns of the bottom plates of the model box (i.e., A→B→C→D→E→F) are shown in **Fig. 5**. The bottom plates #4 and #5 are lowered at the same time with sequences of first, third and fifth (represented as A, C and E), and then bottom plates #3 and #6 are lowered with the sequences of second, fourth and sixth (represented as B, D and F). The stoppage time after each lowering of the bottom plates is left to stabilize the pipe responses (i.e., the increasing of vertical displacement of the pipe is less than 1 mm in 24 hours). The rotation rate of the handle is controlled as 30 rounds/min to lower down the bottom plates with a rate of 3 mm/min. Vaseline is placed on the wall of the model box to minimize the effect of the friction between the side wall and the backfill.

Fig. 5 Moving patterns of the bottom plates (letters A throughout F represent the lowering sequence)

3 Results and Analyses

3.1 Free field soil settlement

Gaussian curves have been widely adopted to predict surface settlement caused by tunneling (e.g., [Peck 1969](#); [Attewell and Farmer 1974](#); [Attewell et al. 1986](#); [Wang et al. 2015](#)):

$$S_v = S_{\max}(\exp(-0.5(x/i)^2)) \quad (1)$$

where $S_{\max}$ is the maximum soil settlement (m); i is the trough width parameter corresponding to the distance from the centerline of the subsidence trough to the point of inflection (m); and x is the distance to the centerline of the ground subsidence zone (m).

Figure 6 shows the variation of the free field settlement at different depth (Z) with lowering sequence of the bottom plates. It is found that **Eq. (1)** does not provide a good prediction of the measured settlement in this study. The fitting by using **Eq. (1)** yields a value of coefficient of determination, R^2 , less than 0.7. Gaussian curves by **Eq. (1)** is not general enough ([Celestino et al. 2000](#)). In this study, a modified five-parameter Gaussian function is developed and expressed by:

$$S_v = mS_{\max}(\exp(-0.5(nx/i+\alpha)^2) + \exp(-0.5(nx/i-\alpha)^2)) \quad (2)$$

$$m = 0.5\exp(0.5\alpha^2) \quad (3)$$

$$\exp(-2n\alpha) (1-(n+\alpha)^2) = (n-\alpha)^2 - 1 \quad (4)$$

where α is a parameter influencing the shape of the curve as shown in **Fig. 7**, and m and n are parameters to ensure that $S_{\max}$ and i remain the maximum soil settlement and the distance to the inflection point, respectively. In this study, $\alpha=0.5$ is assumed.

It is seen in **Fig. 7** that the curvature of modified Gaussian function with $\alpha=1.0$ at $x/i=0$ is smaller than that for the curve with $\alpha=0.5$. In other words, as α increases, the modified Gaussian function becomes flat gradually nearby the maximum soil settlement. **Eq. (2)** reverts to Gaussian function (**Eq. (1)**) for $\alpha=0$.

Fig. 6 Free field soil settlement: (a) $Z=0$ m; (b) $Z=0.3$ m; (c) $Z=0.6$ m; and (d) $Z=0.9$ m (Z represents the initial depth of the settlement plate when the backfilling is completed)

Fig. 7 Influence of α on the modified Gaussian function

Figure 8 shows the variation of the trough width parameter at different depths (denoted as i_{soil}) with lowering sequence of the bottom plates in the free field condition. It is seen that the value of i_{soil} decreases with depth. It illustrates that the settlement tends to spread to a wider range when it propagates upwards to the backfill surface. It is also found that i_{soil} increases when plates #3 and #6 are lowered down at the second, fourth and sixth sequences (represented as B, D and F), while i_{soil} decreases when plates #4 and #5 are lowered down with the sequences of third and fifth (represented as C and E), as compared with the value of i_{soil} with lowering plates #3 and #6 at Sequences B and D.

Fig. 8 Variation of the trough width parameter (i_{soil}) with the lowering sequence of the bottom plates in free field case (“Init.” represents the completion of the backfilling)

Fig. 9 Variation of the maximum soil settlement (S_{max}) with the lowering sequence of the bottom plates in free field case

Figure 9 shows the variation of the maximum soil settlement (S_{max}) at different depths with lowering sequence of the bottom plates. It is seen that the value of S_{max} increases with depth. **Figures 8 and 9** show the settlement troughs become narrower (i.e., i_{soil} decreases) and the maximum settlement becomes larger when burial depth increases. The value of S_{max} increases sharply with the

327 lowering of the bottom plates #4 and #5 at the first, third and fifth sequences (represented by A, C
 328 and E), while it increases slightly with lowering of the bottom plates #3 and #6 with the sequences of
 329 second, fourth and sixth (represented by B, D and F).

330 **Figure 10** presents the variation of the volume of the settlement trough (V_{soil} , unit: m^3/m) at
 331 different depth with lowering sequence of the bottom plates. The volume of the settlement trough
 332 (V_{soil}) is calculated through the integration of **Eq. (2)** and expressed by the following equation:

$$333 \quad V_{\text{soil}} = 2\sqrt{2\pi m} S_{\text{max}} i_{\text{soil}} / n \quad (5)$$

334 It is seen that V_{soil} increases with depth, which is consistent with the change of S_{max} shown in **Fig. 9**,
 335 but opposite to that of i_{soil} shown in **Fig. 8**.

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337

338 **Fig. 10** Variation of the volume of the settlement trough in free field case

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340 3.2 Vertical displacement of the pipes

341 **Figure 11** shows the variation of vertical displacement of the P1, P2, P3 and P4 pipes with
 342 lowering sequence of the bottom plates. **Eq. (2)** is employed to simulate the measured vertical
 343 displacements. **Fig. 12** shows the variations of the maximum vertical displacement of the pipe (S_{pmax})

344 and the maximum free field settlement at the level of pipe axis with lowering sequence of the bottom
 345 plates. The values for S_{pmax} change in the way as: S_{pmax} for P4 < S_{pmax} for P2 < S_{pmax} for P1. This is
 346 consistent with the values of EI of the pipes, i.e., 48 kNm² for P4 pipe, 18 kNm² for P2 pipe, and 5
 347 kNm² for P1 pipe.

348 **Fig. 13** shows that the variation of S_{pmax} normalized by the maximum free filed settlement at the
 349 level of pipe axis with the EI of the pipe. It is seen that the normalized S_{pmax} decreases with EI of the
 350 pipe ($EI_{P1} < EI_{P2} < EI_{P4}$). It is also found from **Fig. 12** that the S_{pmax} values of the P2 pipe (0.6 m
 351 burial depth) are larger than those of the P3 pipe due to the relatively higher burial depth of P3 pipe
 352 (0.9 m). The maximum free field settlement at the level of pipe axis is found to be largest, indicating
 353 that the presence of pipes has limited the settlement of the backfill at the pipe top level.

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Fig. 11 Variation of the vertical displacement of the pipe with the lowering sequence of the bottom plates: (a) P1 pipe, (b) P2 pipe, (c) P3 pipe and (d) P4 pipe

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Fig. 12 Variation of the maximum displacement of pipe with the lowering sequence of the bottom plates

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Fig. 13 Variation of normalized S_{pmax} with bending stiffness of the pipe

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Figure 14 shows the variation of the trough width parameter of pipe displacement profile (i_p)

370

and that of free field settlement trough at the level of pipe axis with lowering sequence of the bottom

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plates. It is seen that the values of i_p change in the way as: i_p for P4 > i_p for P2 > i_p for P1, which is

372 consistent with EI of the pipe, $EI_{P1} < EI_{P2} < EI_{P4}$. The values of i_p for the P2 pipe ($EI = 18 \text{ kNm}^2$ and
373 0.6 m burial depth) are smaller than those for the P3 pipe ($EI = 18 \text{ kNm}^2$ and 0.9 m burial depth),
374 indicating that i_p decreases with burial depth. The trough width parameter of free field settlement
375 trough at the level of pipe axis is found to be the smallest, indicating that the presence of the pipe
376 spreads the soil settlement to a greater width. Stiffer pipe induces wider settlement trough.

378
379 **Fig. 14** Variation of the trough width parameter with the lowering sequence of the bottom plates
380

381 **Figure 15** presents the variation of the volume of the pipe displacement profile (V_p) and that of
382 free field settlement trough at the level of pipe axis. It is seen that the values of V_p values for the P1
383 pipe are larger than those of the P2 pipe, and both of them are larger than those of the P4 pipe. **Fig.**
384 **16** shows the variation of V_p normalized by the volume of free field settlement trough at the level of
385 pipe axis with the EI of the pipe. It is seen that the normalized V_p decreases with EI . It is also found
386 in **Fig. 15** that the V_p values of P3 pipe (burial depth of 0.6 m) are smaller than those of the P2 pipe
387 (burial depth of 0.9 m). The volume of free field settlement trough at the level of pipe axis is found
388 to be larger than all V_p values, indicating that the volume of the settlement trough is reduced with the

389 presence of buried pipes.

390

391

392 **Fig. 15** Variation of the volume of the pipe displacement profile (V_p) with the lowering sequence of
393 the bottom plates

394

395

396 **Fig. 16** Variation of normalized V_p with bending stiffness of the pipe

397

398 3.3 Surface settlement of the backfill above the pipes

399 **Figure 17** shows the surface settlement of the backfill above the P1, P2, P3 and P4 pipes with

lowering sequence of the bottom plates. It is seen that the surface settlements of the backfill measured above the P1 pipe are larger than those above the P2 pipe, and both of them are larger than those above the P4 pipe, which is consistent with the vertical displacements of the pipes shown in **Fig. 11**. The P3 pipe surface settlements are larger than the P2 pipe settlement because of the difference in the vertical distance from the moveable bottom plates to the backfill surface, 0.85 m for the P3 pipe and 1.15 m for the P2 pipe. Soil settlements caused by various lowering sequences of bottom plates over previously consecutive sequence are also shown in **Fig. 11**. It is found that the surface settlement of the backfill above Section 1 of the pipes increases significantly with the second, fourth and sixth sequences of lowering down the bottom plates #3 and #6 (represented by B, D and F). In contrast, only slight increases in the surface settlement are found above Sections 2 and 3 of the pipes when the bottom plates #3 and #6 are lowered down.

413

414

415

Fig. 17 Variation of the surface settlement of backfill with the lowering sequence of the bottom plates: (a) P1 pipe; (b) P2 pipe, (c) P3 pipe and (d) P4 pipe

3.4 Earth pressure

Figure 18 shows the variations of the earth pressures at the top of the P1, P2, P3 and P4 pipes with lowering sequence of the bottom plates. It is seen that the earth pressures measured at the pipe top at Sections 1 and 2 increase with the sequence of lowering the bottom plates. The earth pressures measured at the pipe top at Section 1 increase more significantly with lowering the bottom plates #4 and #5 at the first, third and fifth sequences (represented as A, C and E in **Fig. 16**) than those at Section 2. However, the earth pressures at the pipe top at Section 2 exhibit larger increment than those at Section 1 when lowering the bottom plates #3 and #6 at the sequences of second, fourth and sixth (represented as B, D and F). It is also found from **Figure 18 (d)** that the earth pressures at the bottom of Sections 1 and 2 of the P4 pipe reduce to zero when the bottom plates are lowered down for the first time, indicating that the pipe-soil separation occurs at the bottom of the pipe. It is noted that the earth pressure cells are only installed underneath the P4 pipe.

Fig. 18 Variation of measured earth pressures with the lowering sequence of the bottom plates: (a) P1 pipe; (b) P2 pipe; (c) P3 pipe; and (d) P4 pipe

3.5 Vertical arching factor

Vertical Arching Factor (VAF) at the top of the pipe is calculated by:

$$VAF = P / \gamma H' \quad (6)$$

where P is the earth pressure at the top of the pipe (kPa); γ is the unit weight of the backfill (kN/m³); and H' is the soil cover thickness (m). VAF larger than one indicates that the negative soil arching is

446 triggered at the pipe top.

447 **Figure 19** shows the variation of VAF calculated at the top of the P1, P2, P3 and P4 pipes with
448 the volume of the pipe displacement profile. It is seen from **Fig. 19 (a)** that the values of VAF at the
449 top of the P1 pipe at Sections 1 and 2 are smaller than those of the P2 pipe, and both are smaller than
450 those at the top of the P4 pipe at different lowering sequences of the bottom plates. **Fig. 19(b)** shows
451 that the values of VAF at the top of the P2 pipe at Sections 1 and 2 are smaller than those of the P3
452 pipe. It is concluded that negative soil arching effect at the top of the pipe increases with bending
453 stiffness but decreases with burial depth during localized ground subsidence. [AASHTO \(2012\)](#)
454 recommends the following equation to calculate the VAF at the top of buried flexible pipes:

$$455 \quad VAF = 0.76 - 0.71(S_H - 1.17)/(S_H + 2.92) \quad (7)$$

$$456 \quad S_H = \phi' M_s R / EA \quad (8)$$

457 where S_H is the hoop stiffness factor; ϕ' is the resistance factor for soil stiffness (taken as 0.9); M_s is
458 the constrained soil modulus (kPa); R is the radius from center of pipe to centroid of pipe profile (m);
459 E is the elastic modulus of pipe material (kPa); and A is the gross area of pipe wall per unit length of
460 pipe (m^2/m).

461

Fig. 19 Comparison of the vertical arching factor at the top of the pipes with the volume of pipe displacement profile: (a) P1, P2, and P4 pipes and (b) P2 and P3 pipes

US Committee on Gas and Liquid Fuel Lifelines suggests the following equation to calculate the maximum resistance force for upward movement of the pipe relative to the soil (ASCE 1984):

$$q_u = N_v \gamma H D \quad (9)$$

$$N_v = \phi \gamma / 44 D \quad (10)$$

471 where q_u is the maximum resistance force (kN/m); N_v is a dimensionless factor; γ is the unit weight
472 of the soil (kN/m³); H is the burial depth to the axis of the pipe (m); D is the diameter of the pipe (m);
473 and ϕ is the internal friction angle of the soil (°).

474 The earth pressure at the top of the pipe can be calculated by:

475
$$P=q_u/D \quad (11)$$

476 Substituting **Eq. (11)** into **Eq. (6)** gives the value of VAF .

477 It is seen from **Fig. 19** that the values of VAF calculated by **Eq. (7)** agree well with those
478 measured at the top of the pipes when the backfilling process is completed (i.e., the volume of pipe
479 displacement is zero). However, the calculated values by **Eq. (7)** are 13% to 54% smaller than the
480 measured when the bottom plates are lowered down. The parameters used in **Eqs. (7)** and **(8)** are
481 listed in **Table 4**. For the determination of A value of the pipe wall, double-wall corrugated pipe is
482 idealized as plate elements as per [AASHTO \(2012\)](#). Geometric property (i.e. the A) is determined by
483 the integration of the areas of the corrugations. The elastic modulus of the pipe (E) is taken as 520
484 MPa, representing a secant modulus for one hour, the duration of the model test, based on the time
485 dependent power law model developed by [Chua \(1986\)](#). It is indicated that [AASHTO \(2012\)](#)'s
486 method underestimates VAF at the top of buried pipes when the ground subsidence occurs. The
487 values of VAF calculated by substituting **Eq. (11)** into **Eq. (6)** are 10% and 120% larger than the
488 measured ones. The parameters used in **Eqs. (9) to (11)** are listed in **Table 5**. It is indicated that
489 [ASCE \(1984\)](#) provides a conservative method for the calculation of earth pressure at the top of the
490 flexible pipe subjected to the ground subsidence. This observation is consistent with that reported by
491 [Xie et al. \(2013\)](#) and [Saiyar et al. \(2016\)](#). The reason is that the equations outlined by [ASCE \(1984\)](#)
492 are based on the data from the tests on the rigid pipe, but the resistance force on the pipe increases

with the flexural rigidity of the pipe (e.g., Saiyar et al., 2016).

Table 4 Parameters used in AASHTO (2012)'s method

Pipe ID	M_s (MPa)	R (m)	EA (kN/m)
P1	3.52	0.105	2000
P2	3.52	0.157	3000
P3	3.52	0.157	3000
P4	3.52	0.213	3500

Table 5 Parameters used in the method outlined by ASCE (1984)

γ (kN/m ³)	H (m)	D (m)	ϕ (°)
14.6	0.9	0.4	32.5

4 Discussion

It is seen from Fig. 6 that when the bottom plates #3 and #6 were lowered at Sequence F (i.e., the movable base is 1 m wide), the soil settlement at depth of 0.9 m at 50 mm from side wall of the model box is zero, which means the soil settlement range at pipe axial level (i.e., depth of 0.9 m) is less than 1.9 m wide. Two fixing frames are used to connect the ends of HDPE pipes with the wall of the model box, and a pipe plug mounted on the fixing frame is pushed into the pipe end to simulate a spigot joint. In other words, the vertical displacement of pipe segments adjacent to the test one connected by spigot joints is assumed to be zero in this study. This assumption is considered reasonable because the measured soil settlement range shown in Fig. 6 is less than 1.9 m at pipe axial level (i.e., depth of 0.9 m). In the case that the test pipe longer than 2 m is used and the movable base is still 1 m wide, the vertical displacement profile of the pipe should be the same with the test results presented in this study. This is because the propagation of subsidence to the pipe is only dependent on the width of movable base, and the ranges of soil settlement at the pipe axial level in two cases

should be the same.

Figure 12 shows that the maximum vertical displacements of the P1, P2, P3 and P4 pipes are smaller than the maximum free field settlement at the level of pipe axis. It can be concluded that the pipe deformation caused by the ground subsidence would be overestimated when the free field settlement trough is used. The occurrence of the pipe-soil separation is confirmed from the observation that the earth pressures at the bottom of Sections 1 and 2 of the P4 pipe from 13 kPa are reduced to zero with lowering of the bottom plates, as shown in **Fig. 18 (d)**.

Fig. 18 shows that the earth pressures at the top of the pipes at Sections 1 and 2 are elevated when the bottom plates are lowered down. This is because the settlement of the backfill above the pipe (i.e., Zone B shown in **Fig. 20 (a)**) is smaller than that of its adjacent areas (i.e., Zones A and C) in the transverse direction of the pipe, although the relevant data are not measured in this study. As a result, negative soil arching is triggered at the top of the pipe. More load is transferred to Zone B. It is also found that the earth pressures at the pipe top at Section 1 increase significantly when the bottom plates #4 and #5 are lowering down, while those at the pipe top at Section 2 exhibit a slight increment. This is because the incremental settlements of the backfill above Section 1 of the pipe (i.e., Zone A' shown in **Fig. 20 (b)**) are smaller than those above Section 2 of the pipe (i.e., Zone B') when the bottom plates #4 and #5 are lowered down (See **Fig. 17**). Consequently, more soil load is transferred from Section 2 to Section 1. It is seen from **Figure 19 (a and b)** that VA^F at the pipe top at Sections 1 and 2 are not the same (the differences between two cases are 10% to 21%) with lowering the bottom plates at different sequences. It is thus concluded that the load increment at the pipe top due to localized ground subsidence should be analyzed using a three-dimensional soil arching theory (i.e., soil arching effects in both transverse and longitudinal directions of the pipe). A

study of the effect of localized ground subsidence with the consideration of 3D soil arching will be future research topic.

Fig. 20 Settlement of the backfill in: (a) the transverse direction and (b) the longitudinal direction of the pipe (unit: mm)

A linear regression method is used to correlate the volume of pipe displacement profile with the volume of settlement trough at the backfill surface, as shown in **Fig. 21 (a)**. The slopes of the fitted linear equation for the P1, P2, P3 and P4 pipes are 3.1, 2.8, 2.1 and 1.6, respectively. It is seen from **Fig. 21 (b)** that the gradients of the linear equation decrease with EI of the pipe, but increases with the burial depth. It is seen that if the magnitude of the surface settlement is same, the pipes with larger EI or shallower burial depth are expected to have less deformation. Considering the difficulty in the measurement of pipe responses to the ground subsidence, **Fig. 21** may provide a preliminary method for estimating the deformation of the pipe responding to the ground subsidence. The effect of ground water on the pipe-soil interaction under the localized ground subsidence will be addressed in the further study.

Fig. 21 Relationship of the volume of pipe displacement profile and the volume of surface settlement trough

5 Conclusions

A series of large scale model tests are carried out to investigate the performance of HDPE double-wall corrugated pipes subjected to localized ground subsidence. The variation of earth pressures, the vertical displacements of the pipe, and the settlements of the backfill at different depths for localized ground subsidence are investigated. Based on this study, the following

562 conclusions are drawn:

563 (1) The trough width parameter for the free field soil (i_{soil}) decreases with the depth. It is seen
564 that the soil settlement tends to spread to a wider range when it propagates towards the surface of the
565 backfill. However, both the maximum soil settlement (S_{max}) and volume of the settlement trough
566 (V_{soil}) decrease with the depth.

567 (2) The maximum displacement of the pipe (S_{pmax}) caused by the ground subsidence is smaller
568 than that for the free field soil (i.e., without pipe) at the level of pipe axis. Thus the pipe responses to
569 the ground subsidence will be overestimated by using the free field settlement data.

570 (3) The earth pressure at the bottom of the P4 pipe reduces to zero with lowering the bottom
571 plate. This confirms the occurrence of the pipe-soil separation. Therefore, theory of beams on
572 Winkler elastic foundation is not applicable for the structural responses of buried pipes subjected to
573 ground subsidence, which requires a fully contact condition of soil and structure.

574 (4) The methods outlined by AASHTO (2012) and ASCE (1984) provide lower and upper
575 bounds for the earth pressure at the top of the HDPE pipes subjected to the ground subsidence,
576 respectively. Variation of the earth pressure at the pipe top due to localized ground subsidence should
577 be analyzed with a three-dimensional soil arching theory.

578 (5) Linear equations are established to correlate the volume of pipe displacement profile with
579 the volume of settlement trough at the backfill surface. For the four cases studied, the values for the
580 gradient of the line vary from 1.6 to 3.1, depending clearly on the bending stiffness and burial depth
581 of the pipe. It is seen that the pipes with larger bending stiffness or shallower burial depth would
582 result in less pipe deformation.

583

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585

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592

593 **Notations:**

594 Basic SI units are given in parentheses.

595 A : gross area of pipe wall per unit length of pipe (m^2/m)

596 D : diameter of the pipe (m)

597 E : elastic modulus of pipe material (kPa)

598 H : burial depth to the axis of the pipe (m)

599 H' : soil cover thickness (m)

600 i : trough width parameter corresponding to the distance from the centerline of the subsidence trough
601 to the point of inflection (m)

602 i_{soil} : trough width parameter of settlement profile at the free field soil (m)

603 i_p : trough width parameter of pipe displacement profile (m)

604 m : parameter to ensure S_{max} remain the maximum soil settlement

605 M_s : constrained soil modulus (kPa)

606 n : parameter to ensure i remain the distance from the centerline of the subsidence trough to the
607 inflection point

608 N_v : dimensionless factor

609 P : earth pressure at the top of the pipe (kPa)

610 q_u : maximum resistance force (kN/m)

611 R : radius from center of pipe to centroid of pipe profile (m)

612 S_H : hoop stiffness factor

613 $S_{\max}$: maximum settlement of the free field soil (m)

614 $S_{p\max}$: maximum vertical displacement of the pipe (m)

615 VAF : vertical arching factor

616 V_{soil} : volume of the free field settlement trough at the level of pipe axis (m³)

617 V_p : volume of the pipe displacement profile (m³)

618 x : distance to the centerline of the ground subsidence zone (m)

619 Z : depth of settlement plates (m)

620 α : parameter influencing the shape of the curve

621 γ : unit weight of the backfill (kN/m³)

622 φ : is the internal friction angle of the soil (°)

623 φ' : resistance factor for soil stiffness

624

625 **Abbreviations**

626 AASHTO American Association of State Highway and Transportation Officials

627 ASCE American Society of Civil Engineers

628 HDPE High-Density Polyethylene

629

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Tables Captions

Table 1 Physical properties of the HDPE pipes

Table 2 Gradation characteristics of Yangtze River sand

Table 3 Summary of test cases

Table 4 Parameters used in AASHTO (2012)'s method

Table 5 Parameters used in the method outlined by ASCE (1984)

Figure captions

Fig. 1 Schematic diagram of the model box (unit: mm) (modified from Wang et al. (2015))

Fig. 2 Relationship between the falling height and dry density of the sand

Fig. 3 settlement plate (unit: mm; “y” depends on the distance from the monitoring point to the sand surface)

Fig. 4 Testing instrumentation: (a) P1 pipe; (b) P2 pipe, (c) P3 pipe, (d) P4 pipe and (e) free field (no pipe) (unit: mm)

Fig. 5 Moving patterns of the bottom plates (letters A throughout F represent the lowering sequence)

Fig. 6 Free field settlement: (a) $Z=0$ m; (b) $Z=0.3$ m; (c) $Z=0.6$ m; and (d) $Z=0.9$ m (Z represents the initial depth of the settlement plate when the backfilling is completed)

Fig. 7 Influence of α on the modified Gaussian function

Fig. 8 Variation of the trough width parameter (i_{soil}) with the lowering sequence of the bottom plates in free field case (“Init.” represents the completion of the backfilling)

Fig. 9 Variation of the maximum soil settlement (S_{max}) with the lowering sequence of the bottom plates in free field case

Fig. 10 Variation of the volume of the settlement trough in free field case

Fig. 11 Variation of the vertical displacement of the pipe with the lowering sequence of the bottom plates: (a) P1 pipe, (b) P2 pipe, (c) P3 pipe and (d) P4 pipe

Fig. 12 Variation of the maximum vertical displacement of the pipe with the lowering sequence of the bottom plates

Fig. 13 Variation of normalized S_{pmax} with bending stiffness of the pipe

Fig. 14 Variation of the trough width parameter with the lowering sequence of the bottom plates

Fig. 15 Variation of the volume of the pipe displacement trough (V_p) with the lowering sequence of the bottom plates

Fig. 16 Variation of normalized V_p with bending stiffness of the pipe

835 **Fig. 17** Variation of the surface settlement of backfill with the lowering sequence of the bottom plates:
836 (a) P1 pipe; (b) P2 pipe, (c) P3 pipe and (d) P4 pipe

837 **Fig. 18** Variation of measured earth pressures with the lowering of the bottom plates: (a) P1 pipe; (b)
838 P2 pipe, (c) P3 pipe and (d) P4 pipe

839 **Fig. 19** Comparison of the vertical arching factor at the top of the pipes with the volume of pipe
840 displacement profile: (a) P1, P2, and P4 pipes and (b) P2 and P3 pipes

841 **Fig. 20** Settlement of the backfill in: (a) the transverse direction and (b) the longitudinal direction of
842 the pipe (unit: mm)

843 **Fig. 21** Relationship of the volume of pipe displacement profile and the volume of surface settlement
844 trough