DISCUSSION

Earth pressure measurements on buried HDPE pipe

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The discusser read the paper by Talesnick *et al.* (2011) with interest because of the U.S. Bureau of Reclamation's (USBR's) involvement in analysis, design and construction of buried pipelines for water conveyance related to hydro projects. Laboratory load tests, similar in detail to the ones presented in the paper, were performed in the 1960s by the USBR to investigate soil–structure interaction effects on buried pipelines, and the pressure cells used to measure radial earth pressure were similar in principle to the ones described in the paper (Pettibone & Howard, 1966). Recent numerical analyses of the USBR laboratory model tests on buried concrete pipes using continuum-mechanics-based computer program FLAC (Itasca, 2006) had shown reasonable agreement between the computed and measured radial pressures for loose and compacted backfills (USBR, 2011). This is contrary to the comparisons for the high-density polyethylene (HDPE) pipe reported in the paper. In order to investigate the differences in comparisons, the paper's HDPE pipe was analysed using FLAC; the following two analyses were performed.

(*a*) Analysis A: calculate radial deformations and stresses in the backfill soil at the location of the HDPE pipe (but without the pipe being there) for a select loading sequence used in the paper's laboratory tests.

(*b*) Analysis B: calculate radial deformations and pressures on the HDPE pipe as tested in the paper's laboratory tests.

Both loose and compacted soil conditions were considered in each analysis. The soil–pipe interface was one of zero slip. FLAC analyses are performed in Cartesian (x, y) coordinates. The results (displacements and stresses) were converted into (r, θ) coordinates using appropriate transformations (Gallagher, 1975). Computed results across the vertical diameter line were identical; therefore only one computed value per diagonal is included in the tabulated results. Computed radial compression stresses are shown positive. Measured values shown were scaled from the figures in the paper.

ANALYSIS A

Figure 16 shows the FLAC model; the size and location of the dashed outline in the soil are the same as those of the HDPE pipe in the paper. For this model, only soil properties (density (ρ), E_{soil} and υ_{soil}) were needed; the values given in Table 2 of the original paper were used. The M_s was used

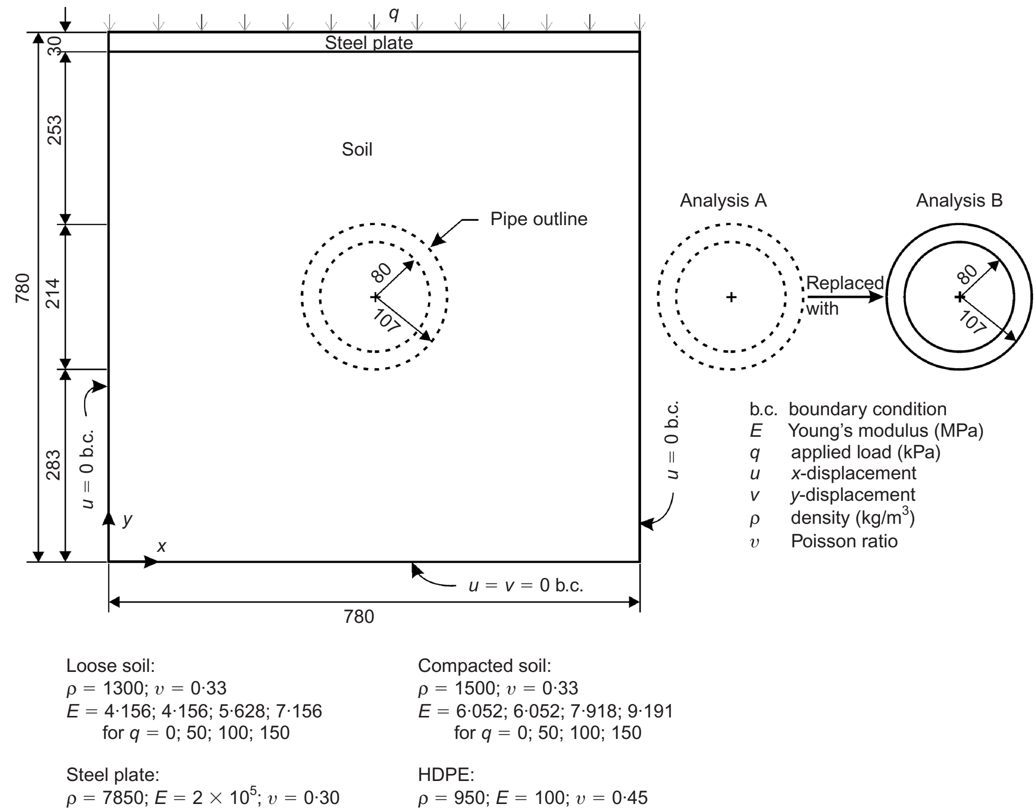

Fig. 16. FLAC model for analysis A and analysis B (all dimensions are in mm)

for E_{soil} because M_s was obtained from the load–settlement test data and its use as E_{soil} (without adjustments by way of υ_{soil}) in plane strain analysis was considered appropriate. The top three rows of the grid in Fig. 16 were assigned $\rho = 7850\ \mathrm{kg/m^3}$, $E = 200$ GPa and $\upsilon = 0{\cdot}30$ to simulate a 30 mm thick steel platform for the applied load (q) used in the laboratory test set-up. The loading sequence used was $q = 0$, 50, 100 and 150 kPa.

The computed diameter deflections in the soil for the vertical, horizontal and diagonal diameters along the $r = 80$ mm outline are summarised in Table 4; and the computed radial stresses in the soil at the locations of the earth pressure cells along the $r = 107$ mm outline are summarised in Table 5. The paper's measured values for the HDPE pipe deflections and earth pressures are included in Tables 4 and 5.

Significant observations from these results for the loose and compacted backfills include the following points.

(*a*) The computed vertical diameter deflections in the soil at $r = 80$ mm are similar in magnitude and direction to the paper's measured values for the HDPE pipe.
(*b*) The computed diagonal diameter deflections in the soil at $r = 80$ mm are similar in direction, but not in magnitude, to the paper's measured values for the HDPE pipe.
(*c*) The null values for computed horizontal diameter deflections are as expected.
(*d*) The computed radial stresses in the soil at $r = 107$ mm are similar to the paper's measured values for the HDPE pipe; the only gross exception to this is at $\theta = 270°$ location for the compacted backfill.

ANALYSIS B

Figure 16, with the substitution shown therein, also serves as the FLAC model for analysis B. The properties for the soil and steel plate are the same as for analysis A. The HDPE was assigned $\rho = 950\ \mathrm{kg/m^3}$, $E = 0{\cdot}1$ GPa and $\upsilon = 0{\cdot}45$. The tensile modulus for HDPE material ranges from 0·18 to 1·6 GPa (Samborsky, 2012); $E = 0{\cdot}1$ GPa was used considering the analysis A results, and to account for the effects of alterations made to the HDPE pipe for instrument installations. The loading sequence used was $q = 0$, 50, 100 and 150 kPa.

Results of analysis B are shown in Tables 6 and 7, and Fig. 17. Significant observations from these results for the loose and compacted backfills include the following points.

(*a*) The HDPE pipe moderates the deformations and stresses in the backfill.
(*b*) The computed vertical and horizontal diameter deflections compare better to their measured counterparts than do the diagonal diameter deflections for the loose backfill.

Table 4. Summary of computed diameter deflections in the soil along the $r = 80$ mm outline (Fig. 16) and measured deflections of the HDPE pipe

Backfill	Diameter orientation	Diameter deflections: mm computed*/measured†			
		Applied vertical stress, q: kPa			
		0	50	100	150
Loose	Vertical (90–270°)	−0·12/0	−1·34/−1·00	−2·37/−2·00	−3·11/−3·00
	Horizontal (0–180°)	0/0	0/0·80	0/1·50	0/2·20
	Diagonal (45–225°), (135–315°)	−0·06/0, 0	−0·71/−0·03, 0	−1·25/−0·07, 0	−1·65/−0·14, −0·01
Compacted	Vertical (90–270°)	−0·09/0	−1·03/−0·63	−1·69/−1·42	−2·25/−2·17
	Horizontal (0–180°)	0/0	0/0·66	0/1·30	0/2·00
	Diagonal (45–225°) or (135–315°)	−0·05/0·03	−0·54/−0·14	−0·89/−0·39	−1·19/−0·68

* Computed values are from FLAC analyses of the soil mass and are adjusted to three significant digits.
† Measured values are of the HDPE pipe and are scaled from Figs 5(b) and 5(d) and Figs 7(b) and 7(d) in the original paper.

Table 5. Summary of computed radial stresses in the soil along the $r = 107$ mm outline (Fig. 16) and measured radial pressures on the HDPE pipe

Backfill	Location	Radial stress/pressure: kPa Computed*/measured†			
		Applied vertical stress: kPa			
		0	50	100	150
Loose	Crown ($\theta = 90°$)	3/0	52/68	107/110	157/155
	Shoulder ($\theta = 45°$, 135°)	3/0, 0	39/48, 36	80/93, 73	118/138, 119
	Springline ($\theta = 0°$, 180°)	2/0, 0	26/36, 36	54/69, 66	79/105, 95
	Haunch ($\theta = 225°$, 315°)	4/0, 0	40/36, 76	81/77, 124	119/127, 161
	Invert ($\theta = 270°$)	6/0	55/60	109/142	160/210
Compacted	Crown ($\theta = 90°$)	4/0	57/89	107/164	157/228
	Shoulder ($\theta = 45°$, 135°)	3/0, 0	43/27, 43	80/49, 98	117/76, 147
	Springline ($\theta = 0°$, 180°)	3/0, 0	29/30, 30	54/64, 54	79/88, 88
	Haunch ($\theta = 225°$, 315°)	5/0, 0	45/32, 32	82/60, 69	119/83, 103
	Invert ($\theta = 270°$)	7/0	61/18	111/37	160/59

* Computed values are from FLAC analyses of the soil mass and are adjusted to the nearest whole number.
† Measured values are of the HDPE pipe and are scaled from Figs 5(a) and 5(c) and Figs 7(a) and 7(c) in the original paper.

Table 6. Summary of computed and measured diameter deflections of the HDPE pipe ($r = 80$ mm)

Backfill	Diameter orientation	Diameter deflections: mm Computed*/measured†			
		Applied vertical stress, q: kPa			
		0	50	100	150
Loose	Vertical (90–270°)	−0·06/0	−1·21/−1·00	−2·31/−2·00	−3·19/−3·00
	Horizontal (0–180°)	0·02/0	0·65/0·80	1·18/1·50	1·55/2·20
	Diagonal (45–225°), (135–315°)	−0·02/0, 0	−0·28/−0·03, 0	−0·57/−0·07, 0	−0·82/−0·14, −0·01
Compacted	Vertical (90–270°)	−0·07/0	−1·10/−0·63	−1·92/−1·42	−2·66/−2·17
	Horizontal (0–180°)	0·02/0	0·50/0·66	0·81/1·30	1·06/2·00
	Diagonal (45–225°) or (135–315°)	−0·02/0·03	−0·31/−0·14	−0·56/−0·39	−0·80/−0·68

* Computed values are from FLAC analyses and are adjusted to three significant digits.
† Measured values are scaled from Figs 5(b) and 5(d) and Figs 7(b) and 7(d) in the original paper.

Table 7. Summary of computed and measured radial pressures on the HDPE pipe ($r = 107$ mm)

Backfill	Location	Radial stress/pressure: kPa Computed*/measured†			
		Applied vertical stress: kPa			
		0	50	100	150
Loose	Crown ($\theta = 90°$)	3/0	53/68	105/110	151/155
	Shoulder ($\theta = 45°$, 135°)	4/0,0	47/48,36	95/93,73	138/138,119
	Springline ($\theta = 0°$, 180°)	2/0,0	42/36,36	87/69,66	129/105,95
	Haunch ($\theta = 225°$, 315°)	3/0,0	47/36,76	95/77,124	138/127,161
	Invert ($\theta = 270°$)	4/0	53/60	106/142	152/210
Compacted	Crown ($\theta = 90°$)	3/0	55/89	99/164	142/228
	Shoulder ($\theta = 45°$, 135°)	4/0,0	52/27,43	94/49,98	136/76,147
	Springline ($\theta = 0°$, 180°)	3/0,0	48/30,30	90/64,54	131/88,88
	Haunch ($\theta = 225°$, 315°)	4/0,0	52/32,32	94/60,69	136/83,103
	Invert ($\theta = 270°$)	4/0	56/18	100/37	143/59

* Computed values are from FLAC analyses and are adjusted to the nearest whole number.
† Measured values are scaled from Figs 5(a) and 5(c) and Figs 7(a) and 7(c) in the original paper.

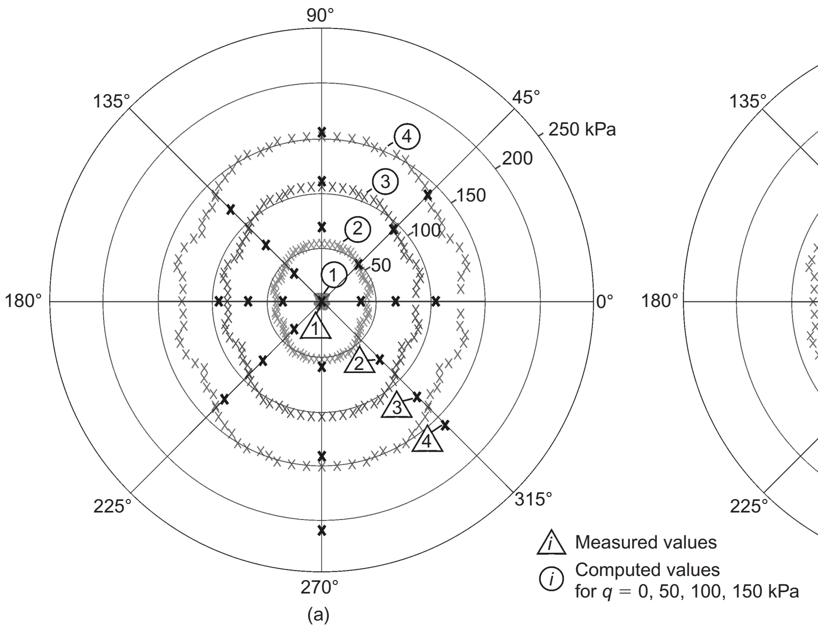

Fig. 17. Results of analysis B: (a) radial pressures on the pipe at $r = 107$ mm in the loose backfill; (b) radial pressures on the pipe at $r = 107$ mm in the compacted backfill

(*c*) The computed radial stresses on the pipe are comparable to their measured counterparts; significant exceptions to this are at $\theta = 270°$ location for the loose backfill and $\theta = 90°$ and 270° locations for the compacted backfill.
(*d*) The computed radial stresses on the pipe for the compacted backfill are similar to those for the loose backfill.

SUMMARY OF FINDINGS

The computed and measured deformations of the buried HDPE pipe are not large enough to cause substantial redistribution of pressures at the soil–pipe interface for the applied loads. Important parameters affecting the computed results are the physical properties of the pipe and the soil. Except for the size of the pipe and *E* of the backfill, other material properties used in FLAC models are essentially estimated values. Also, there are lapses in the paper's laboratory test set-ups. The vertical forces on the pipe inferred from the measured pressures do not satisfy equilibrium. This could be due to side shear that was not measured, or some large inaccuracies in the pressure measurements. Thus, the measurements presented in the paper appear to omit a major component of vertical force on the HDPE pipe.

Authors' reply

The authors would like to thank the discusser for his interest in the submission. It is the authors' opinion that the data collected for the radial pressure felt by the pipe are of very high quality and represent a true measure of what the pipe feels when loaded at the points measured. Furthermore, the data illustrate that the installation procedures, most importantly the tamping process, have a significant effect on the relative magnitude of the radial pressures felt at different points around the pipe.

Elastic analyses are unable truly to represent the effects of installation procedures, rather they can only model increased stiffness and strength of the pipe bedding and backfill. For this reason elastic computations will invariably result in symmetrical or near-symmetrical distributions of radial pressures about the horizontal axis of the pipe. This was the result seen by using Hoeg (1968) for a pipe in linear elastic material as presented in the paper, and the result obtained by the discusser when using FLAC (Itasca, 2006) modelling the soil as a linear elastic material.

Construction effects result in radial pressure measurements that do not illustrate symmetry about the horizontal axis. This does not mean that vertical equilibrium is not met. Shear around the pipe circumference and complex distributions of radial pressure (not fully demonstrated by the measurements made at the eight locations) cannot be accounted for.

The discusser has referred to experiments reported by Pettibone & Howard (1966). These experiments were performed with rigid concrete pipes, yet the resulting pressure measurements illustrate a remarkably similar outcome to those presented by the authors. Those radial pressure measurements illustrate a lack of symmetry about the horizontal axis (see Figures 4–9 in Pettibone & Howard (1966)); moreover the location of the maximum recorded radial pressure changes from the crown to the invert as placement conditions were varied. This type of response can only be represented if the construction sequence is modelled.

In closure, the soil and the pipe do not know that the soil is supposed to behave elastically; therefore they do not respond as the software system would have the user believe. On the other hand, reliable pressure measurements may help better understanding of how installation procedures and varied soil density, particle arrangement and stiffness will affect the response of flexible pipe to external loading.

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