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STUDY ON THE SEISMIC DESIGN OF POLYETHYLENE PIPE DURING AN EARTHQUAKE

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Abstract

Evaluation of the seismic performance of a buried pipeline changes depending on whether the pipe slips against the surrounding soil. When slippage occurs, stress and strain concentrate on junctions and bends. Important factors as to whether slippage occurs are the critical shear stress of the soil (τ_{cr}) and the elasticity of the pipe materials. Since there were few reports of experiments regarding τ_{cr} of polyethylene pipe (HPPE), we conducted experiments to investigate the performance of HPPE.

Our results are as follows: (1) τ_{cr} of HPPE (straight pipe) is approximately 10 kN/m^2 under 60 cm of backfilling soil. Therefore, we adopted a τ_{cr} of 10 kN/m^2, which comes from the experiments with steel pipe, although there is a large difference in elasticity between HPPE and steel pipe. This means that the existing seismic design method for buried pipelines can be applied to HPPE. (2) τ_{cr} of HPPE with accessories including an Electric Fusion(EF) coupler and branch saddle rise to 10.8 kN/m^2–19.5 kN/m^2 because these accessories become the resistance in the soil. (3) We found that even HPPE can slip by approximately 12 mm in solid ground, which is approximately 1/20 of the maximum slippage of steel pipe. It was considered that the slippage of HPPE has little influence on junctions and bends.

Keywords: buried pipeline; polyethylene pipe; critical shear stress; slippage effect

1. Introduction

The method of evaluation in the seismic design of a buried pipeline depends on whether the pipe slips against the surrounding soil. If slippage occurs, stress and strain concentrate in the junctions and bends. If there is no slippage, stress and strain concentrate in the pipe-itself [1, 2]. In seismic design in Japan, HPPE is categorized as a pipe which slippage does not occur because of the pipe's elasticity. Regrettably, a seismic design method for HPPE has not been sufficiently established in Japan because there is not enough experimental evidence about slippage.

Therefore, the purpose of this study is to determine the slippage between the HPPE and surrounding soil during severe earthquakes by measuring τ_{cr} of straight pipe and with an EF coupler and branch saddle. Then we also confirm the possibility of slippage for HPPE in various types of ground.

2. Seismic design of buried pipeline

2.1 Seismic design method of polyethylene pipeline

The Response Displacement Method is commonly used to evaluate the seismic design of buried pipelines in Japan. This method estimates the ground motion and displacement of pipelines. With regard to ground motion, we have typically used a seismic velocity of 100 kine (cm/s) after the Great Hanshin Earthquake of 1995.

In this section, we discuss the current evaluation method for buried HPPE in Japan. The evaluation method for buried pipelines is detailed in the seismic design guidelines for water–works facilities, which are published by the Japan Water Works Association (JWWA). With regard to guideline, Fig. 1 shows a ground model for buried pipelines. The ground model is composed of surface ground and base rock. This model assumes soft ground because there is serious damage in soft ground. As this model shows, we estimate the seismic response displacement by using a deep soft-ground model to resist a large displacement. The strain of the pipelines is calculated with ground displacement U_h and ground strain ε_G. U_h and ε_G are expressed as Eq. (1) and Eq. (2), respectively:

$$U_h = \frac{2}{\pi^2} S_v T_G \cos\left(\frac{\pi}{2H} h'\right) \tag{1}$$

$$\varepsilon_G = \eta \frac{2\pi}{L} U_h \tag{2}$$

If a severe earthquake of 100 kine (cm/s) occurs in the model, the ground displacement U_h and ground strain ε_G are, respectively, calculated as 0.31 m and approximately 1%, when $\eta = 2.0$, which considers a high non-uniformity ground. Additional seismic data are the wavelength L = 194m, response velocity spectrum S_v = 100 cm/s, typical period of the surface ground T_G = 1.54 s, thickness of surface ground H = 30 m, and soil depth of pipe center h' = 0.69 m. We assume HPPE with an outer diameter of 0.18 m is buried under 60 cm of backfilling soil in the model. The pipe material used is used PE100. Table 1 shows the seismic calculations for HPPE. From this table we can confirm the strain of HPPE is 1% as well as the ground strain because the ground strain directly transfers to HPPE. Consequently, HPPE is safe against severe earthquakes because the strain caused during an earthquake is small compared with the permissible strain (3%) of HPPE. A stress and strain curve for HPPE is shown in Fig. 2. A Permissible strain of 3% is determined by performing a repeated stress test that applies a strain of ±3%.

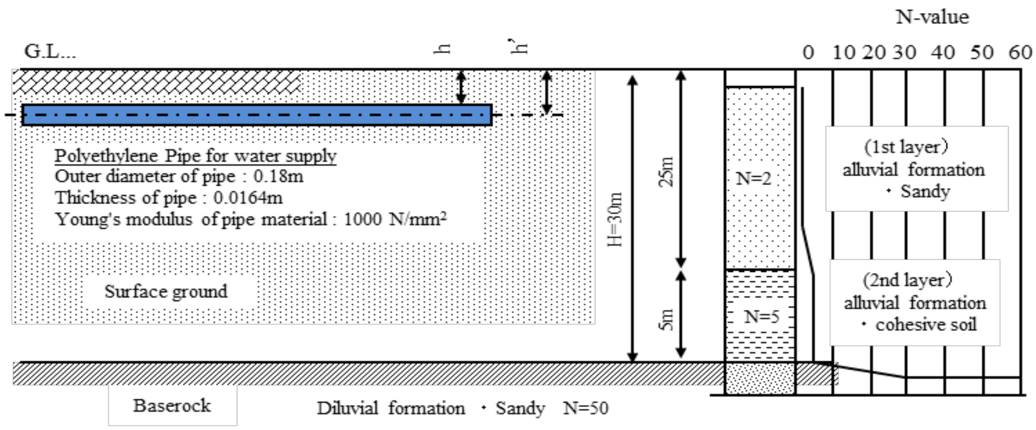


Fig. 1 – Ground model for buried pipelines

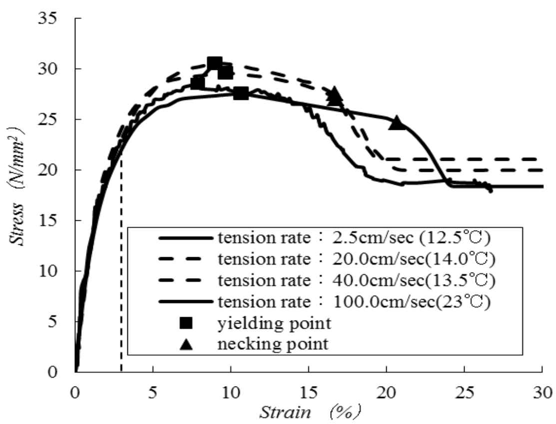


Fig. 2 – Stress-strain curve of HPPE

Table 1 – Seismic calculation of HPPE

Seismic calculation Level 2 ground motion (Sv=100kine)		HPPE
Ground strain ε_G (η =2.0)		1.0%
Slip or not	τ_G =3.8kN/m^2	$\tau_G < \tau_{cr}$
	τ_{cr} =10kN/m^2	not slip
Strain of pipe (without permanent loading)		1.0%
Permissible strain of HPPE		3.0%

2.2 Slippage between pipe and the surrounding soil

Slippage between pipes and the surrounding soil is an important factor in seismic design. Slippage can be judged by comparing shear stress τ_G produced interface between pipe and surrounding soil with a critical shear stress τ_{cr}. The shear stress τ_G acting on the pipe surface is given by Eq. (3) where L' is apparent traveling wavelength, E is Young's modulus of the pipe material, t is thickness of pipe, α_1 is conversion factor for pipes and ε_G is ground strain. Note that the modulus of elasticity of HPPE is 200 times smaller than that of steel pipe.

If $\tau_G \geqq \tau_{cr}$, slippage will take place.

If $\tau_G \leqq \tau_{cr}$, slippage will not take place.

$$\tau_G = \frac{2\pi}{L'} \times E \times t \times \alpha_1 \times \varepsilon_G \tag{3}$$

In Fig. 1, the shear stress τ_G of HPPE is calculated as 3.8 kN/m^2. Meanwhile, the seismic design guidelines of the Japan Water Works Association and Japan Gas Association show that the critical shear stress τ_{cr} is approximately 10 kN/m^2 depending on the depth of the backfilling soil [2, 3]. Therefore, HPPE does not slip because τ_G is smaller than τ_{cr}.

However, we have no experimental evidence about the τ_{cr} of HPPE. Thus, we performed an experiment determine the τ_{cr} of HPPE. First, we performed an experiment with a straight pipe of HPPE. In general, HPPE is jointed with an EF coupler at least every 5 m and with a branch saddle installed at least every 10 m. We thought that these accessories became a resistance in the soil during an earthquake. Then we performed experiments with accessories including an EF coupler and branch saddle.

3. Measuring test of critical shear stress τ_{cr}

3.1 Outline

The HPPE is buried in a soil box that is made of steel (length: 1.6 m × width: 0.9 m × height: 1.1 m). The relative displacement between the pipe and the soil is caused by loading in the axial direction with an oil jack (capacity: 100 kN, length of stroke: 200 mm). The soil box with the pipe with accessories (for example, an EF coupler) is buried. The measuring instruments are shown in Fig. 3. Accessories are installed at 0.4 m from the edge of the soil box. The load is measured by a load cell (capacity: 50 kN), which is installed at the blind flange. The displacement between the pipe and soil is measured by two displacement meters. Picture 1 shows the details of the loading position. Table 2 shows the loading speed of each test. The loading speed is a static condition that matches past experiments with steel pipe.

There are three types of specimens: straight pipe, pipe with EF coupler (Picture 3) and pipe with a branch saddle (Picture 4). The branch saddle is made of cast iron and fastened with a standard tightening torque of 40 N･m. HPPE is drilled through the branch saddle under water pressure, assuming a water supply state. The nominal diameters of the pipes used in the experiments are 50 A and 200 A, and the standard dimension ratio (SDR) is 11. The pipes are buried with backfilling soil at depths of 30 cm, 60 cm, and 120 cm. We examine whether the depth of the soil has an influence on τ_{cr} by changing the depth of the backfilling soil. The 30-cm soil depth of the pipes is backfilled with river sand. Backfilling with a depth of more than 30 cm is reproduced by loading the upper load, as shown in Picture 2. In addition, a 60-cm depth of backfilling soil is standard in Japan. The results of soil test are shown in Table 3. In general, HPPE is backfilled with river sand in Japan. The degree of soil compaction is controlled by more than 90%.

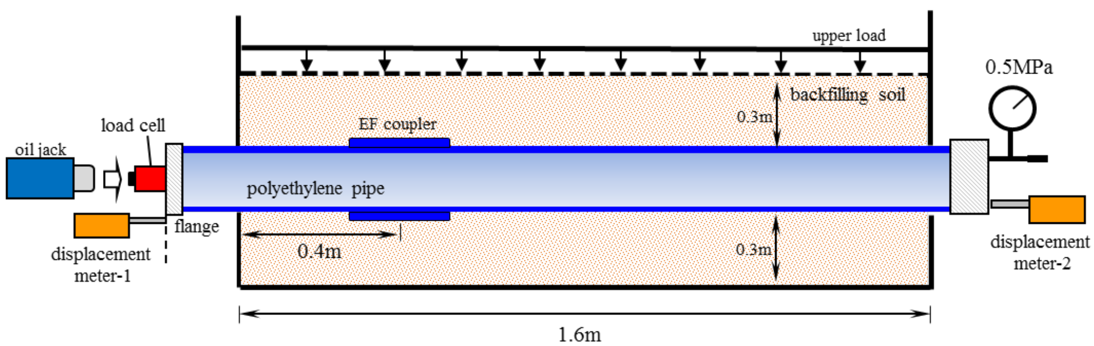


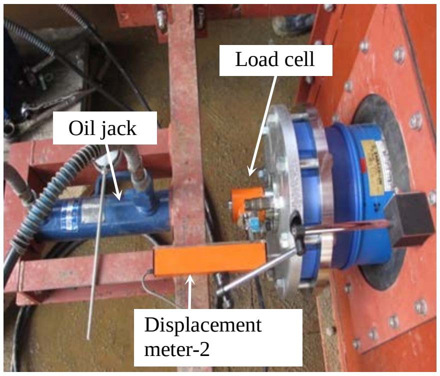
Fig. 3 – Soil box and measuring instruments (e.g., pipe with EF coupler)

Table 2 – Test conditions and loading speeds

Loading speed (mm/s)	50 A (O.D 63)			200 A (O.D 250)		
	Depth of backfilling soil			Depth of backfilling soil		
	30 cm	60 cm	120 cm	30 cm	60 cm	120 cm
Straight pipe	7.8	8.2	7.3	15.2	2.0	13.3
	7.3	6.4	5.9			
Pipe with EF coupler	12.0	11.5	11.3	8.9	4.4	6.1
		11.4			10.8	
Pipe with a branch saddle	–	11.2	–	–	9.8	–

Table 3 – Results of soil test

Contents of test (River sand)		Result
General	Density of the sand	2.69 g/cm^3
	Water content	11.8%
Compaction	Maximum dry density	1.72 g/cm^3
	Optimum water content ratio	13.8%
Tri-axial compression	Adhesive force	1.9 kN/m^2
	Internal frictional angle	36°



Picture 1 – Loading position (200 A)

Picture 2 – Loading upper load

Picture 3 – Pipe with EF coupler (200 A)

Picture 4 – Pipe with a branch saddle (200 A)

3.2 Results of the test

3.2.1 Straight pipe

Fig. 4 and Fig. 5 show the relationship between the shear stress and relative displacement of 50 A and 200 A, respectively. Shear stress is determined by dividing the load by the surface area of the pipe in the sand box. From these figures, we find that the shear stress converges to a constant value after slippage and is proportionate to the depth of the backfilling soil. This tendency is also shown in the seismic design guidelines of the Japan Gas Association [4].

Next, we summarize the relationship between the depth of the backfilling soil and the critical shear stress in Fig. 6 and Table 4. In this result, we find that the critical shear stress τ_{cr} of HPPE is 8.70–11.23 kN/m^2 (average 10.3 kN/m^2) for backfilling soil with a 60-cm depth, which is standard in Japan. The current seismic design guidelines for a water supply show a τ_{cr} of approximately 10 kN/m^2 regardless of the material of the pipes. We proved there is no difference in τ_{cr} between HPPE and steel pipe, although there is a considerable difference in elasticity between HPPE and steel pipe. Therefore, the results of this experiment indicate that the τ_{cr} of the current guidelines is also valid for HPPE.

Using these figures, we examined the ground spring coefficient. Taking account of the bi-linear approximation, these figures show that the point of slippage δ_{cr} has an estimated displacement of no less than 2–4 mm. In this study, we approximate a bi-linear line that is equal to the original curve. In the result, the displacement, which evaluates points of slippage between the soil and HPPE, are 2.7 mm–3.4 mm at a 60-cm depth of backfilling soil.

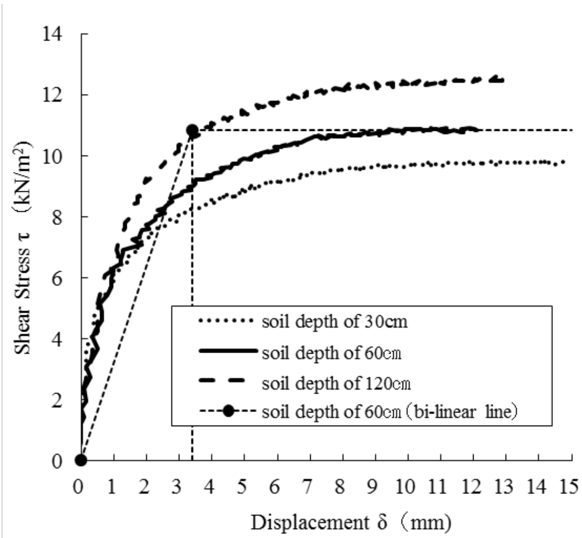


Fig. 4 – Shear stress-displacement curve (50 A)

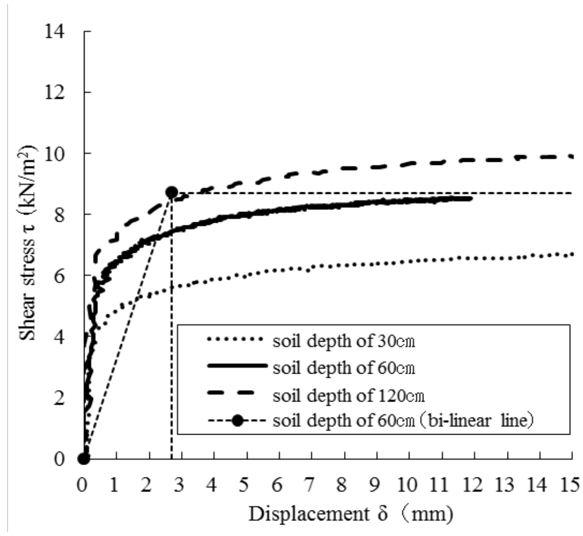


Fig. 5 – Shear stress-displacement curve (200 A)

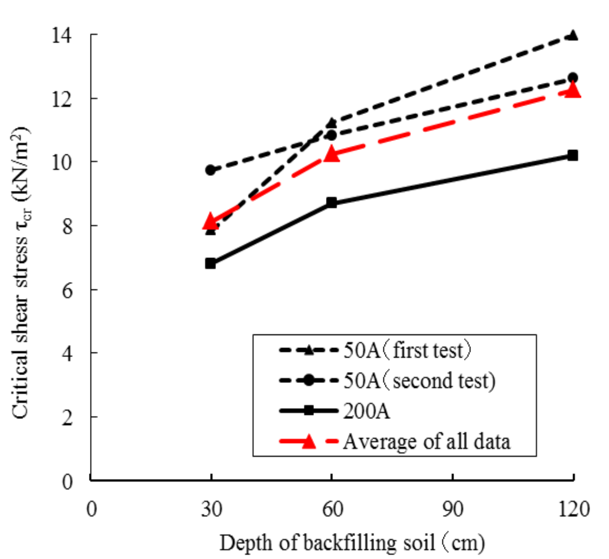


Fig. 6 – τ_{cr} vs. depth of backfilling soil

Table 4 – Critical shear stress of straight pipe

Depth of backfilling soil (cm)	Nominal Diameter	τ_{cr} (kN/m^2)	δ_{cr} (mm)	k (N/cm^3)
30	50	7.86	–	–
		9.75	3	3.25
	200	6.81	2.2	3.09
60	50	11.23	–	–
		10.83	3.4	3.19
	200	8.7	2.7	3.22
120	50	13.99	–	–
		12.63	3.6	3.51
	200	10.2	3.2	3.19

3.2.2 Pipe with EF coupler and branch saddle

In general, HPPE is jointed with an EF coupler at least every 5 m and a branch saddle installed at least every 10 m in a real pipeline. Then these accessories become the resistance in the soil. Fig. 7 and Fig. 8 show the relationship between the shear stress and displacement of HPPE with accessories. For comparison, we also show the results for straight pipe in these figures. From these figures, the shear stress of HPPE with accessories increased after slippage. This is because these accessories became a resistance. In addition, we confirmed that there was no leakage from the branch saddle at a 100 mm displacement because the branch saddle has enough constraint force.

Now we make a synthetic curve to determine the τ_{cr} of HPPE with accessories. The synthetic curve is plotted by adding the results from straight pipe to the resistance of the EF coupler and branch saddle. From the synthetic curve, we think that the shear stress at a point of 20-mm displacement is appropriate as τ_{cr} of HPPE, taking into consideration the resistance of accessories, if we assume we are examining a real pipeline [5]. Therefore, we determined τ_{cr} of HPPE, assuming a real pipeline, as shown in Table 5. The results show that a τ_{cr} of 50A is larger than that of 200 A. This is because the ratio between the hanging area of the accessories and the surface area of the pipe at approximately 50 A is relatively larger than that at 200 A.

Note that the shear stress of a synthetic curve keeps increasing at a 100-mm displacement, contrary to our expectations. We considered that this increase could be attributed to the boundary condition of the soil box. The influence of the boundary condition is the subject of further study.

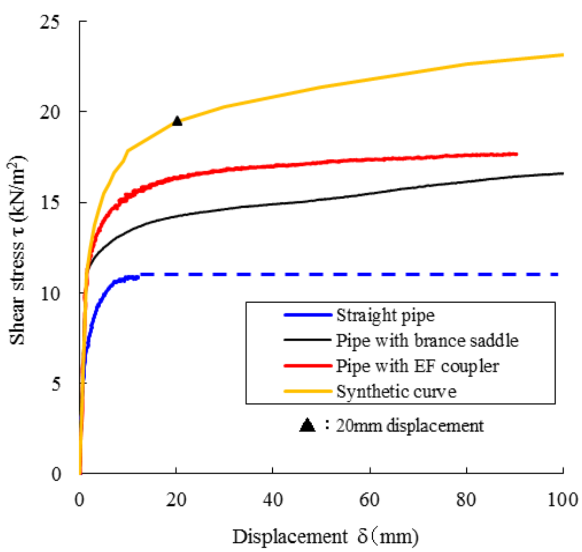


Fig. 7 – Shear stress-displacement curve (50 A)

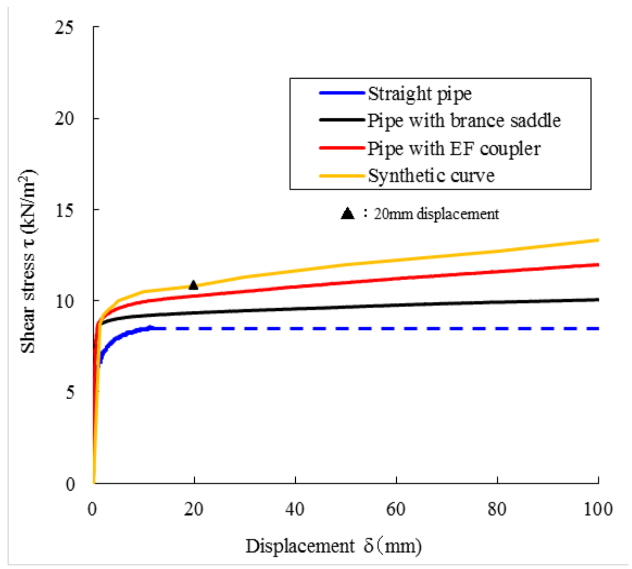


Fig. 8 – Shear stress-displacement curve (200 A)

Table 5 – τ_{cr} of HPPE (kN/m^2)

	50 A	200 A
20-mm displacement	19.5	10.8

4. Relative displacement when slippage takes place

In this section, we discuss whether HPPE slips against the surrounding soil in various types of ground during a severe earthquake. We confirmed that HPPE does not slip in Fig. 1. However, the possibility that slippage takes place depending on the type of ground cannot be denied. Thus, in Table 6, we list three different types of ground models in addition to those in Fig. 1. Model 4 is the most solid ground in these models. The slippage can be judged by comparing τ_G and $\tau_{cr.}$

We summarized τ_G and the relative displacement during a severe earthquake in Table 7. If τ_G is smaller than τ_{cr}, slippage does not take place. Thus, we indicated "no slip" in the lower row. On the other hand, the relative displacement is calculated if slippage takes place. The relative displacement is given by Eq. (4). Here we adapted τ_{cr} = 10.8 kN/m^2 regardless of the pipe diameter. This is the minimum value we obtained from the HPPE experiments. From this table, we found that τ_G became large in case with solid ground and a large diameter of pipe. Moreover, even HPPE can slip by approximately 12 mm in solid ground because τ_G becomes large. This is approximately 1/20 of the maximum slippage of steel pipe under the same conditions. It is considered that a 12-mm slippage of HPPE has little influence on junctions and bends.

$$\Delta = (1-\alpha^*)\times U_h \tag{4}$$

in which the slippage factor q^* is related to τ_G/τ_{cr} in the following manner:

$$\alpha^* = q^* \times \alpha_0$$

$$\tau_G \geq \tau_{cr}, \quad q^* = \sin\xi \times \left(1+\frac{\pi}{8}-\frac{\zeta^2}{2}\right) - \zeta \times \cos\zeta$$

$$\xi = \arcsin\left(\frac{\tau_{cr}}{\tau_G}\right)$$

Table 6 – Ground model

Ground model	Thickness of surface ground (m)		Ground motion lever 2 (Sv = 100 kine)
	1st layer Sandy (N = 2)	2nd layer Cohesive soil (N = 5)	
model 1 (Fig.1)	25m	5m	Wavelength L=194.2m Typical period T_G=1.54s Ground displacement U_h=31.2cm
model 2	10m	5m	Wavelength L=134.4m Typical period T_G=0.7s Ground displacement U_h=14.1cm
model 3	5m	5m	Wavelength L=61.7m Typical period T_G=0.42s Ground displacement U_h=8.5cm
model 4	0m	5m	Wavelength L=27.3m Typical period T_G=0.14s Ground displacement U_h=2.8cm

Table 7 – Shear stress τ_G and relative displacement (τ_{cr} = 10.8 kN/m^2)

Ground model		Upper: Shear stress τ_G (kN/m^2) Lower: Relative displacement (mm)				
		50 A	75 A	100 A	150 A	200 A
model 1 (Fig.1)	25 m	1.3	1.9	2.6	3.8	5.2
	5 m	no slip	no slip	no slip	no slip	no slip
model 2	10 m	2.5	3.9	5.4	7.7	9.9
	5 m	no slip	no slip	no slip	no slip	no slip
model 3	5 m	3.6	5.1	7.1	10.2	14.1
	5 m	no slip	no slip	no slip	no slip	12.1
model 4	0 m	6.0	8.5	11.8	16.9	23.4
	5 m	no slip	no slip	1.0	7.3	12.5

5. Conclusion

Our conclusions are as follows: (1) τ_{cr} of HPPE (straight pipe) is 8.70–11.23 kN/m^2 (average 10.3kN/m^2) under 60 cm of the backfilling soil. We proved that there is no difference in τ_{cr} between HPPE and steel pipe, although there is a large difference in elasticity between HPPE and steel pipe. This means the existing seismic design methods for buried pipeline can be applied to HPPE. (2) τ_{cr} of HPPE with accessories (including EF coupler and branch saddle) rises to 10.8 kN/m^2–19.5 kN/m^2 because these accessories become the resistance in the soil. (3) We found that even HPPE can slip by approximately 12 mm in solid ground, which is approximately 1/20 of the maximum slippage of steel pipe. It was considered that the slippage of HPPE has little influence on junctions and bends.

6. Acknowledgements

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Appendix

Nomenclature used in this paper is summarized as follows:

U_h : ground displacement

S_v : response velocity spectrum

T_G : typical period of the surface ground

H : thickness of the surface ground

h' : soil depth of pipe center

E : Young's modulus of the pipe material

L : wavelength

L' : apparent traveling wavelength

τ_{cr} : critical shear stress

τ_G : shear stress produced on the pipe surface during earthquake

t : thickness of pipe

α_1 : conversion factor for pipes

η : non-uniformity coefficient of ground

ε_G : ground strain