INTERNATIONAL SOCIETY FOR SOIL MECHANICS AND GEOTECHNICAL ENGINEERING

The paper was published in the proceedings of the 7th Australia New Zealand Conference on Geomechanics and was edited by M.B. Jaksa, W.S. Kaggwa and D.A. Cameron. The conference was held in Adelaide, Australia, 1-5 July 1996.

Deformation of HDPE Drainage Pipes Buried under High Fills in Centrifuge Models

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Summary Deformation behavior of HDPE (High Density Poly-Ethylene) drainage pipes under high fills was investigated through centrifuge model tests. In the tests, a dry sand was backfilled to form trapezoidal shapes around model HDPE pipes; fills were constructed around the backfilled areas with three different soils; lead shot was placed on the fill surfaces to create overburden pressures equivalent to those due to prototype fills with heights up to 100 m. Pipe deflections measured in a centrifugal acceleration environment did not conform to those calculated in accordance with the Japanese current design standard based on Marston-Spangler theory. The tests showed that the deflection of the HDPE pipes should be controlled to be less than 10 % for long-term stability. Several measures to avoid buckling failures in the HDPE pipes, installed on hard subsoils and on soft fills, were discussed on the basis of the test results.

1. INTRODUCTION

Due to its high flexibility to cope with large ground deformation, HDPE corrugated pipes are increasingly being used for drainage under 20 m-50 m high fills at mountain-side land reclamation sites in Japan (Ohi et al. 1991). However, behavior of the HDPE pipes buried under such high fills has not been made clear, resulting in excessive deformations at several sites as shown in Fig. 1. Thus, a series of centrifuge model tests was conducted to investigate the deformation behavior of the HDPE pipes buried under high fills.

In the tests, two model HDPE pipes having external diameters of 2.26 cm were surrounded with a dry sand to form trapezoid shapes, and 10 cm high fills were constructed over them with three different soils; lead shot was placed on the fill surfaces to create overburden pressures due to prototype high fills up to 100 m. Models were subjected to a centrifugal acceleration environment, and vertical deflections of the model pipes were measured at every 10 g until the centrifugal acceleration reached 100 g (g: gravitational acceleration).

The tests fully quantified effects of both fill materials and bedding thicknesses on the pipe deflections, whereas the Design Standard of MAFF (Japanese Ministry of Agriculture, Forestry and Fisheries 1988) did not conform to the test results. Buckling in the model pipes was observed in several tests, the data of which yielded a recommendation that the deflection of the HDPE pipes should be controlled to be less than 10 % for the long-term stability. Several measures to avoid the buckling in the HDPE pipes, installed on hard subsoils and on soft fills, were discussed on the basis of the test results.

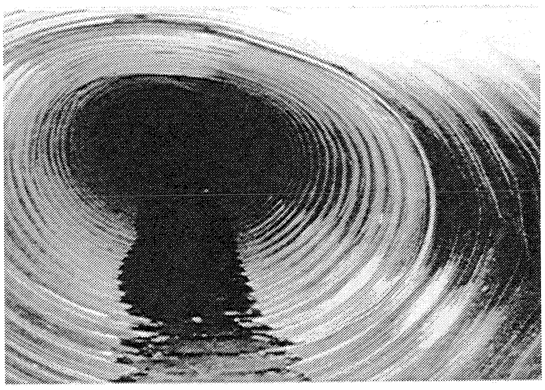


Figure 1. Excessive deformation of HDPE pipe.

2. MODEL, EQUIPMENT AND TEST PROCEDURE

Actual HDPE pipes to be simulated in the centrifuge model tests have corrugated wall profiles and an identical flexural stiffness, S_p, of 0.56 kgf/cm^2 (= 54.9 kPa) in any diameter; this S_p value was obtained by two-edge loading tests through $S_p = 0.149P/\Delta D$, in which P is a concentrated line load applied on the top and bottom of the pipe, and ΔD is the measured vertical deflection.

Fig. 2 shows a model pipe, which was made of a HDPE water main pipe specified in JIS K 6762. The external diameter, D, length, L, and wall thickness, t, of the model pipe are 22.6 mm, 149 mm, and 0.9 mm, respectively. Although the wall

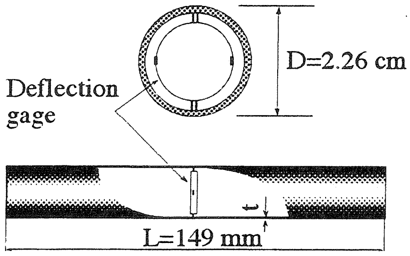


Figure 2. Model HDPE pipe.

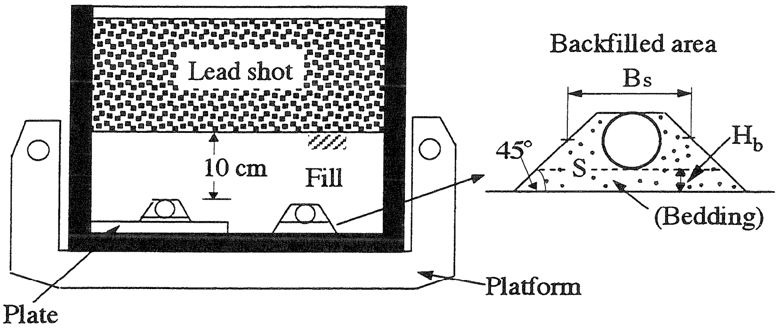


Figure 3. Models and test setup.

profiles of the actual HDPE pipes are corrugated, the wall of the model pipe was finished to be plane and smooth to avoid difficulty in manufacturing. Its thickness, t=0.9 mm, was determined to achieve $S_p=0.56$ kgf/cm^2, which is identical with that of the actual HDPE corrugated pipes; S_p in the model pipe is defined as $E_p t^3/\{12(1-\nu_p^2)\}/R^3$, where E_p and ν_p: Young's modulus and Poisson's ratio of HDPE, and R: neutral radius of the pipe. A ring-type deflection gauge with a light weight was mounted inside the model pipe to measure change in its vertical diameter, ΔD.

Fig. 3 shows a 2-D model and test setup. A test container used in the tests was made of hard aluminum alloy, whose inside dimensions were 45 cm in width, 30 cm in height and 15 cm in thickness. A 15 cm high steel box was mounted on the container as a collar. As shown in Fig. 3, two model pipes were set on sand beddings having different thicknesses H_b of 0.5 cm (H_b/D=0.22) and 2 cm (H_b/D=0.88), which were directly constructed on the bottom of the container to simulate a condition that the pipes were installed on a hard subsoil. To simulate the pipe installation usually adopted in actual construction, furthermore, a dry sand was loosely backfilled around each pipe to form a trapezoidal shape with a slope angle of 45 degrees and a width B_s of 2D at the pipe springline; this trapezoid-shaped area including the bedding was named as a backfilled area. The fill 10 cm high was constructed around the backfilled areas with soils. Lead shot was placed on the fill surface to create overburden pressures equivalent to those due to the self-weights of prototype fills with heights up to 100 m. The effect of using the lead shot was investigated in the preliminary tests as described later.

The soils used in the tests were dry silica sand (S), decomposed granite (G), and silty sand (F), whose properties are shown in Table 1 and Table 2. The main difference between these soils is the amount of fine graded fractions, together with water contents. S, G and F contain the fine graded fractions of 0 %, 16 %, and 30 %, respectively; their water contents are 0 %, 10 %, and 12 %. The soil S was commonly used in the whole tests as bedding and backfill materials; the three soils, S, G and F, were used as fill materials.

The model was prepared in accordance with the following procedure:

The inside wall of the test container was lubricated by means of two sheets of latex membrane 0.2 mm thick with silicon grease to minimize the friction force acting on it. In the tests using the soils G and F as the fill materials, the model pipes were set inside the aluminum spacers, whose shapes are coincident with those of the backfilled areas, and the soil was loosely placed outside the spacers by light compaction to the heights of the spacers. After the spacers were removed carefully, the soil S was poured into the backfilled areas by using a small hopper. The loose fill 10 cm thick was constructed by light compaction every 2 cm layers afterward. In the tests using the soil S as the fill material, the soil was poured into the container from 1 cm height with a small hopper having a circular hole of 1 cm diameter. The compaction and pouring of the soils were performed in the vertical direction as in actual construction. The density of each soil was checked during the model construction. After the completion of the fill, lead shot was placed on its surface to have a density ρ=6.87 g/cm^3. The thicknesses of the

Table 1. Primary properties of soils.

Soil	G_s	Particle size Max. mm	 75μm> %	U_c	ρ_{dmax} g/cm^3	ρ_{dmin} g/cm^3	w_{opt} %
S	2.65	1.4	0	1.75	1.58	1.32	-
G	2.71	2.0	16	70	1.92	1.37	11.4
F	2.67	2.0	30	115	1.86	1.18	13.5

Table 2. Properties of model fills.

Soil	Density$^{1)}$	w %	ρ_d g/cm^3	$D_r$$^{2)}$ %	$c_d$$^{3)}$ tf/m^2	$\phi_d$$^{3)}$ degree
S	Loose	0	1.43	47	0	37
G	Loose	10	1.50	30	0.9	38
	Dense		1.70	68	2.3	38
F	Loose	12	1.50	58	3.0	32
	Dense		1.70	84	4.6	32

1) Dense grounds were used for additional tests; 2) D_r: Relative density; 3) Shear strength parameters under consolidated-drained condition.

lead shot layers were selected for their combination with the 10 cm fills to create the overburden pressures equivalent to those due to soil fills with heights, H, of 10 cm, 20 cm, 40 cm, 70 cm, and 100 cm (H/D=4.4, 8.8, 17.7, 31, and 44).

The models were subjected to a centrifugal acceleration environment by using a centrifuge located at Osaka City University; its nominal radius is 2.56 m, the maximum acceleration being 200 g. The centrifugal acceleration was increased 10 g step wise until it reached 100 g. The vertical deflections of the model pipes were recorded by a digital strain meter 3-4 minutes later after the centrifugal acceleration was reached every 10 g. In two special tests with H/D =44 using the soil F, the holding time every 10 g was extended as 30 minutes to investigate an increase in the pipe deflection against the elapsed time; these tests are named as long-term tests.

Table 3 summarizes the test conditions, together with those of the preliminary tests. The total number of the tests was 26.

Table 3. Test Conditions.

(a) Preliminary test

Soil	Density	Lubrication & lead shot	H/D	H_b/D	B_s/D
F	Loose	With Without	4.4 - 17.7	0.22 0.88	2

(b) Primary test

Soil	Density	H/D	H_b/D	B_s/D
F,G,S	Loose	4.4 - 44	0.22 0.88	2

3. RESULTS OF PRELIMINARY TEST

Preliminary tests were carried out to investigate effects of the lubrication and using the lead shot on the pipe deflection. Fig. 4 shows pipe deflection ratios $\delta=\Delta D/2R$ (R: neutral radius of the model pipe) against H/D measured at 100 g in the preliminary tests with $H_b/D=0.22$, in which "without the lead shot" means that the model ground was constructed with the soil only. The figure shows that: (1) when the lubrication was not applied, δ with the lead shot was greater than δ without it (▲>■), and (2) δ with the lubrication was always greater than δ without it (△>▲ and □>■). As a result, when the lubrication was applied, δ with the lead shot was almost coincident with δ without it (△≒□). Similar results were obtained for $H_b/D=0.88$. Thus, the effect of using the lead shot on the test results can be neglected, if the lubrication is applied as in the primary tests described below.

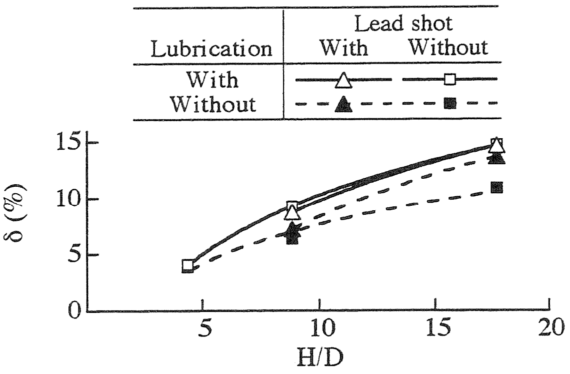


Figure 4. δ vs H/D in preliminary tests ($H_b/D=0.22$).

4. RESULTS OF PRIMARY TEST

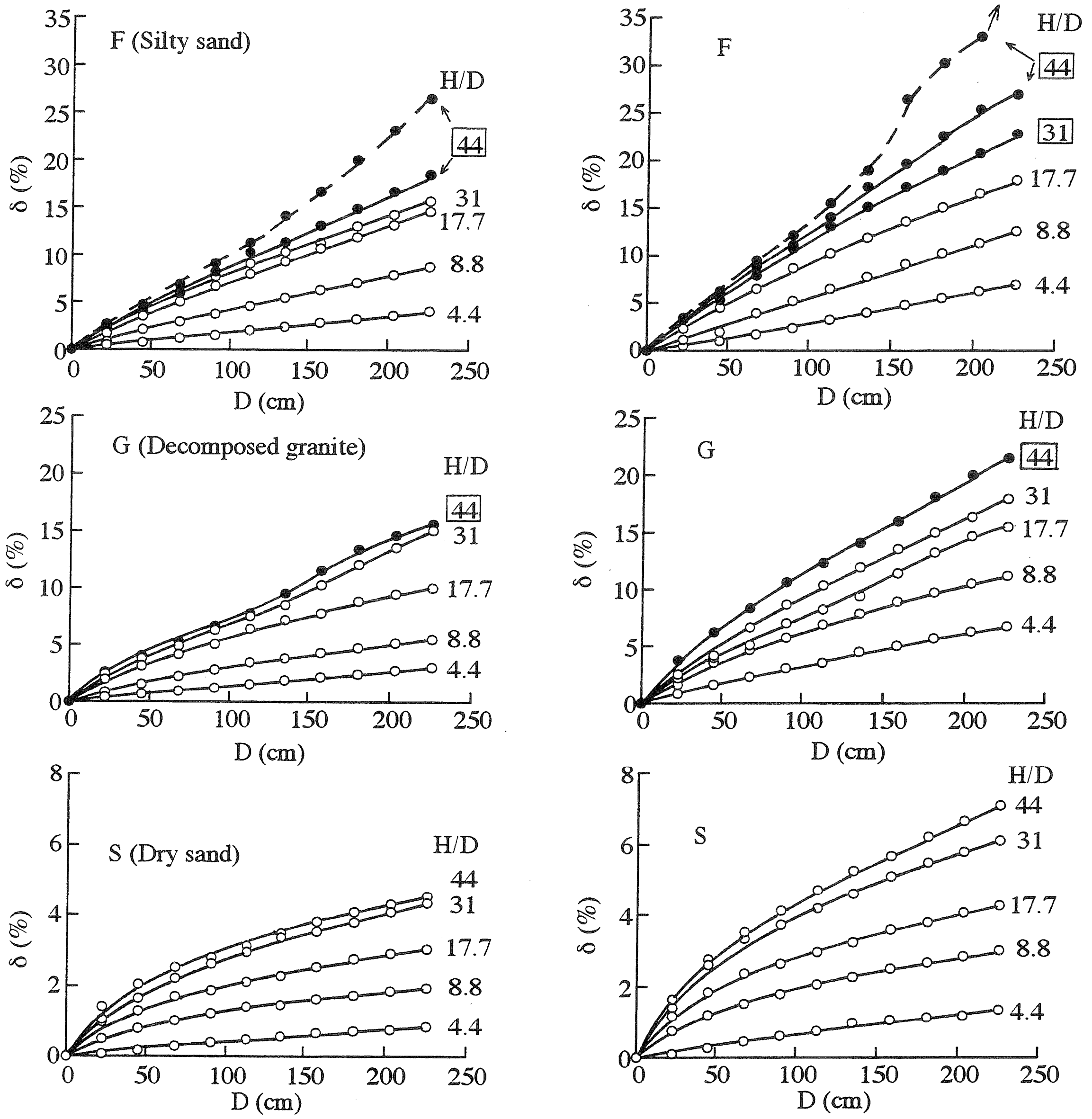
Fig. 5 illustrates δ-D curves, measured for the three fill soils with different H_b/D and H/D, in the prototype scale. Two broken-line curves for the soil F with H/D=44 correspond to the data measured in the long-term tests. The marks ●, furthermore, show the data when buckling at the top of the pipe was observed after the test; the pipes deformed to be heart-shaped, as shown in Fig. 6, in five tests using the soil F and in a test using the soil G with H_b/D =0.88. In a test using the soil G with $H_b/D=0.22$, a tiny line was observed on an inner surface of the top of the pipe. The figure shows that:

1) δ was smaller, when the fill soil contained less amount of the fine graded fractions and the bedding thickness was smaller.
2) When the pipes were not buckled, the δ-D curves decreased their inclinations with an increase in D.
3) Among 7 curves when the pipes were buckled, the two δ-D curves for the long-term tests increased their inclinations when δ>15 %, and the remaining five curves generated the maximum δ greater than 15 %. This suggests that the pipes must have been buckled at δ≒15 %.

Fig. 7 plots δ against the elapsed time T, measured at every 10 g in the long-term tests with $H_b/D=$ 0.88. The data within 50 g, considered as an elastic range in the pipe, generated relationship between Δδ (increment in δ) and T (min.) as $\Delta\delta(\%)=0.38\log_{10}T$. The data for $H_b/D=0.22$ generated almost the same relationship. Through this equation, Δδ after 50 years was calculated as 2.8 %. This Δδ must have been produced by creep in both the pipe material and soil.

5. DISCUSSIONS AND MEASURES

The test results showed that the model grounds, constructed with the soils containing less fine graded fractions, generated smaller δ. Fig. 8 shows deformation moduli E_s and Poisson's ratios ν_s of the three soils under the loose conditions used in the tests. These data were obtained through K_0-compression tests using a rectangular rigid box, as shown in



(a) $H_b/D=0.22$

(b) $H_b/D=0.88$

Figure 5. δ vs D for different fill materials (☐ : Pipe was buckled).

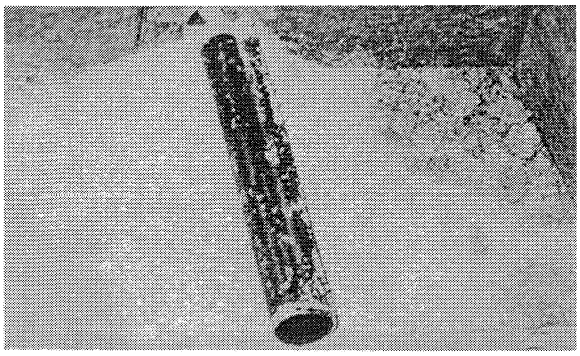


Figure 6. Buckling failure of model pipe.

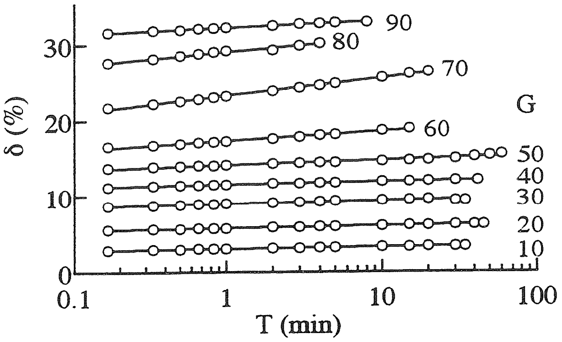


Figure 7. δ vs T measured in the long-term test ($H_b/D=0.88$).

the figure; the soil specimen had dimensions of 12 cm × 12 cm in area and 10 cm in height (Tohda et al. 1995). In the tests, axial strain ε_1 and lateral stress σ_3 were measured under K_0-condition (= null lateral strain condition) when axial stress σ_1 was applied step wise. E_s and ν_s were calculated through the equations shown in the figure, which were derived from the Hooke's law. Fig. 8 indicates that the soils containing less fine graded fractions have greater E_s values and produce smaller δ in the tests.

Fig. 9 compares δ measured at 100 g (D=2.26 m and H=100 m in the prototype scale) with δ calculated in accordance with the design standard of MAFF,

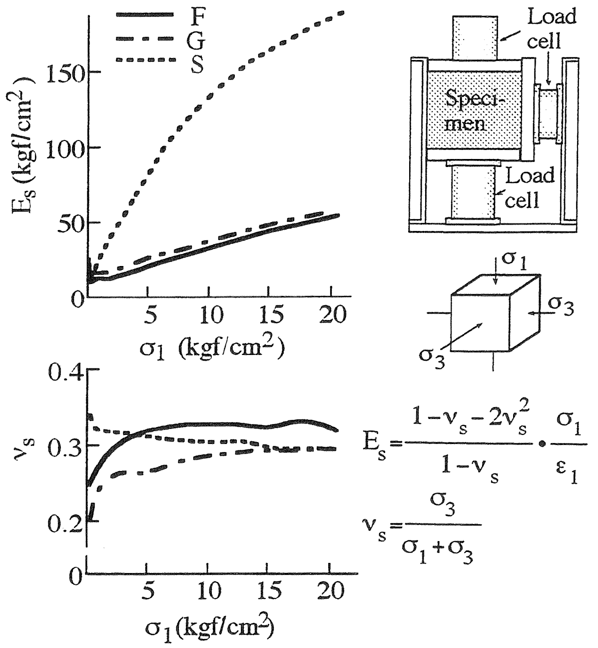


Figure 8. E_s and ν_s of three soils measured through K_0-compression test (1kgf/cm^2 =98kPa).

which is based on Marston-Spangler theory. It is usually assumed in the actual design procedure that the pipes are fully supported with the backfill soils when the pipes are installed in the trapezoidal backfilled-areas as in the present tests. Thus, comparing a dotted design line for the soil S with all the measured δ, the design line does not conform to the test results in any case. A similar conclusion is obtained when comparing the measured δ with three design lines, which were calculated with an assumption that the backfilled areas do not exist. It is better, therefore, to use Fig. 5 rather than the current design, when predicting deflections of the HDPE pipes installed under conditions similar to the present test conditions.

The data shown as the marks ● in Fig. 5 suggest that the HDPE pipes may be safe just after the completion of the construction if their δ are controlled to be less than 15 % during the construction. When the pipes are used during 50 years after the construction, however, $\Delta\delta$=2.8 % obtained from the long-term tests should be subtracted from δ=15 %. Considering the safety factor, the authors recommend that the maximum δ at the construction should be controlled to be less than 10 % for the long-term stability of the HDPE pipes. This also means that some countermeasures are necessary for such construction conditions that δ was recorded greater than 10 % in Fig. 5. The following three measures can be considered for such cases: (1) widening the backfilled area, (2) densifying the backfill sand, and (3) densifying the fill. Here, effects of (1) and (3) on δ were investigated through additional centrifuge model tests with H/D=44 (Series A and B), whose conditions are shown in the upper two columns of Table 4. Figs. 10 and 11 show measured δ in these test series, indicating the effectiveness of these countermeasures.

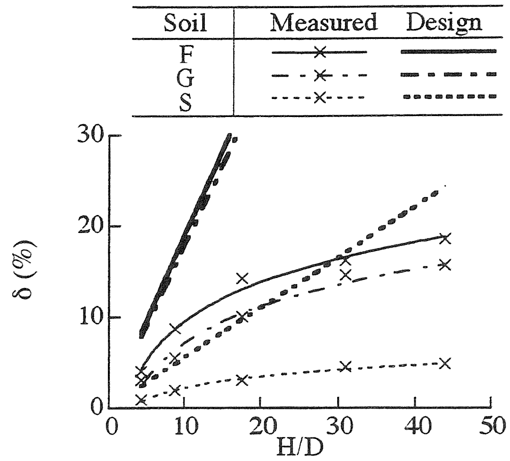


Figure 9. Comparison of measured δ for H_b/D=0.22 with design values.

Finally, the test results showed that the thinner the bedding thickness, the smaller δ it generates. Therefore, the pipes should be installed on sand beddings as thin as possible. In turn, this suggests that δ will

Table 4. Conditions of additional tests.

Series	Soil	Density	H/D	H_b/D	B_s/D	H_s/D
A	F	Loose	44	0.22 0.88	2 3 4	0
B	F,G	Loose Dense	44	0.22 0.88	2	0
C	F	Loose	44	0.22	2 3	0 1.1 2
D	F	Loose	44	0.22	2 3	2*

* Including base concrete under the backfilled area.

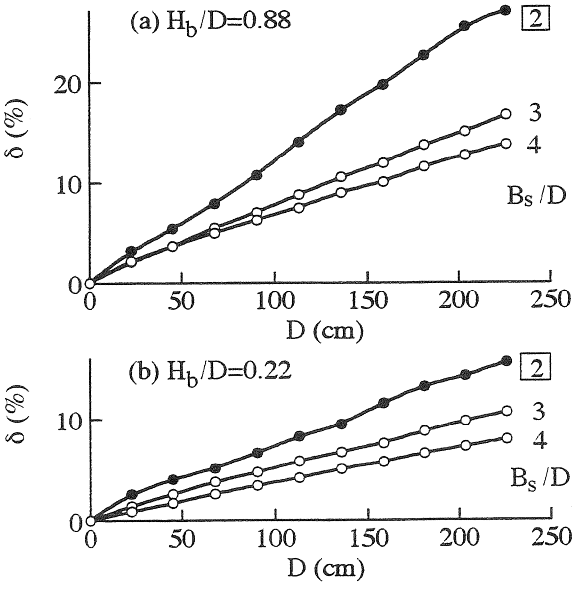


Figure 10. δ vs D for different B_s /D (Series A).

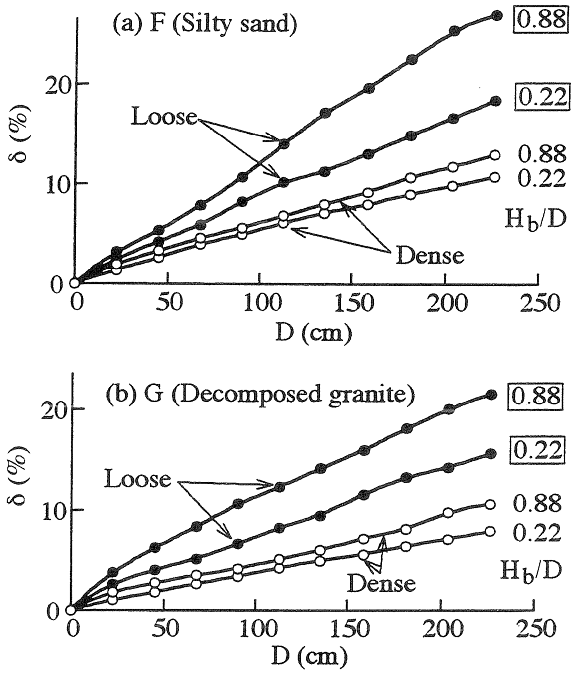
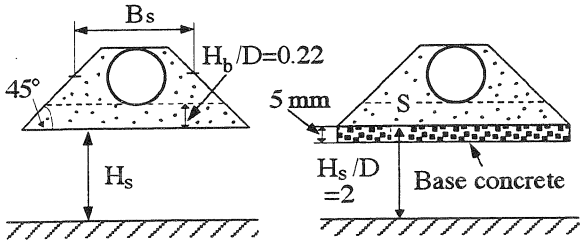


Figure 11. δ vs D for different ground densities (Series B).

increase when the pipes are installed on soft soil layers instead of hard subsoils. To confirm this, the other additional tests (Series C) were carried out, in which the model pipes were installed on the loose soil F layers having different thicknesses, H_S, as shown in Fig. 12 (a); the conditions in this test series are shown in Table 4. Fig. 13 shows δ measured in Series C, indicating that δ increased with an increase in H_S/D, as expected. The authors invented a measure for this critical pipe installation to place base concrete under the backfilled area, as shown in Fig. 12 (b), and conducted Series D tests with $H_S/D=2$ to confirm its effectiveness. The tests generated δ illustrated as marks × in Fig. 13. The δ drastically decreased its value to be almost coincident with δ for $H_S/D=0$ when the pipe was installed on the hard subsoil, though the pipe was buckled when $B_S/D=2$.

6. CONCLUSIONS

Deformation behavior of HDPE drainage pipes buried under high fills was investigated through centrifuge model tests, in which a dry sand was backfilled to form trapezoid shapes around the model HDPE pipes. The following conclusions can be drawn from this study:



(a) Series C (b) Series D

Figure 12. Pipe installation on loose soil F layer.

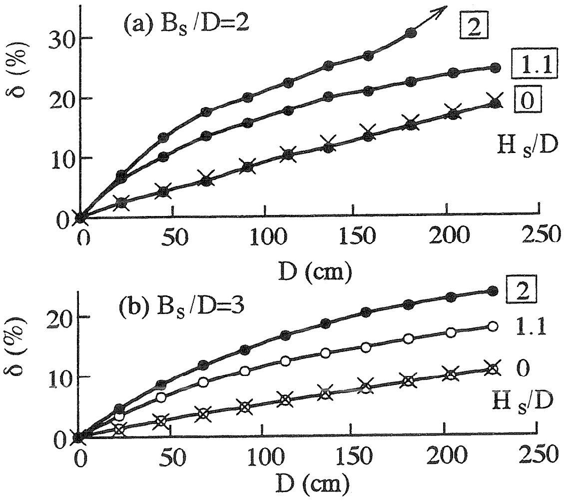


Figure 13. δ vs D for different H_S/D in Series C and D (×: Series D, $H_S/D=2$).

1) To avoid buckling failure in the HDPE pipes, the pipe deflections just after the construction should be controlled to be less than 10% for the long-term stability.

2) Vertical deflections of the HDPE pipes, installed on hard subsoils, become smaller, when the fill material contains less amount of fine graded fractions and the bedding thickness is smaller.

3) When the pipes are installed on hard subsoils, both widening the backfilled area and densifying fills are effective to decrease the pipe deflections.

4) When the pipes are installed on soft soil layers, the pipe deflections are considerably greater than those when the pipes are installed on hard subsoils. They increase with an increase in thicknesses of soft soil layers. In this critical pipe installation, placing base concrete under the backfilled area, together with widening the backfilled area, must be adopted to avoid the buckling failure of the pipes.

5) Since the current design based on Marston-Spangler theory showed a poor agreement with the test results, it is better to use the test results shown in this paper for predicting the deflections of the HDPE pipes installed under the conditions similar to the test conditions.

7. REFERENCES

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