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Response and design of buried pipelines subjected to differential ground settlement

Réponse et plan du tuyau installé dans un terrain qui entraîne le tassement différentiel

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ABSTRACT
A series of 3-D centrifuge model tests on buried pipelines generated detailed data of both distribution of earth pressure along the pipe long axis and non-linear change in the pipeline response (earth pressure and deflection) due to increase in differential ground settlement. A new design method that considers both high earth pressure concentration onto the upper-half of pipeline and change in the extent of the area with the pressure concentration was proposed. Its validity was confirmed through comparison with the test results.

RÉSUMÉ
Une série d'essais des modèles centrifuges du 3-D a montré des données détaillées des distributions de la poussée du terrain au long de l'axe du tuyau et du changement non-linéaire dans la réponse du tuyau (la poussée du terrain et la déformation) qui est issue de l'agrandissement du tassement différentiel. Nous avons proposé un nouveau plan qui tient compte de la forte concentration des conteraintes sur la moitié haute du tuyau, et du changement de la hauteur où la poussée est concentrée. Sa validité a été confirmée en comparaison avec les résultats des essais.

1 INTRODUCTION

Differential ground settlement has often caused damage to small diameter buried pipelines (JSGE 1979, Tohda et al. 1991, Selvadurai et al. 1993). Recently this also caused damage to large diameter pipelines, including water main pipelines (Tohda & Hachiya et al. 2000) and pipe culverts crossing highway fills. Sluiceway pipelines crossing fill dams or canal dikes also have been damaged. In spite of these accidents, mechanical response (earth pressure and deflection) of pipelines subjected to differential ground settlement has not been studied appropriately, because it is governed by complicated 3-D soil-pipe interaction involving many variables. As a result, any rational design method for buried pipelines had not been developed.

Therefore, a series of 3-D centrifuge model tests was first conducted to investigate actual response of buried pipelines. The tests generated detailed data of both distribution of earth pressure along the pipe long axis and non-linear change in the pipeline response due to increase in differential ground settlement. The tests also quantified the effects, on the pipeline response, of several critical factors such as ground conditions, burial dimensions of pipelines, and pipe flexibilities. It was found that a pair of 3-D ground arch, produced by the differential ground settlement, generated high earth pressure concentration onto the upper-halves of pipelines. Second, a new rational design method for buried pipelines was developed based on observations made in the centrifuge tests. The method was validated using model test results.

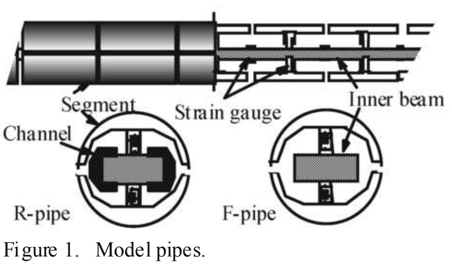


Figure 1. Model pipes.

Table 1. Specifications of pipes.

Pipe	D_m (cm)	EI_m ($N{\cdot}m^2$)	W_m (N/m)	D_p (cm)	EI_p ($MN{\cdot}m^2$)	W_p (N/m)
R	2	28	0.067	60	23	60
F	2	5.9	0.057	60	4.8	51

Subscripts, m and p, denote model and prototype.
W denote pipe weight.

2 3-D CENTRIFUGE MODEL TESTS

2.1 *Experimental procedures*

Figure 1 shows 1/30-scaled two model aluminum pipes used in the tests. They were named as F-pipe and R-pipe according to their flexibilities. Each pipe consisted of an inner beam and half-cylindrical-shaped segments. The inner beam was 590 mm long and had a rectangular section of 12 mm in width and 4.5 mm in height (h). Fifty-six, 20 mm long segments with smooth surfaces were fixed by means of small prismatic bars to the upper and lower surfaces of the inner beam to form a circular pipe which was 580 mm long with a 20 mm external diameter (D_m). Table 1 shows specifications of the pipes.

The segment and prismatic bar assembly formed a load cell to measure vertical and tangential earth pressures (p and τ) acting on the pipe through axial and bending strains produced in the prismatic bars. Furthermore, strain gauges were glued on the

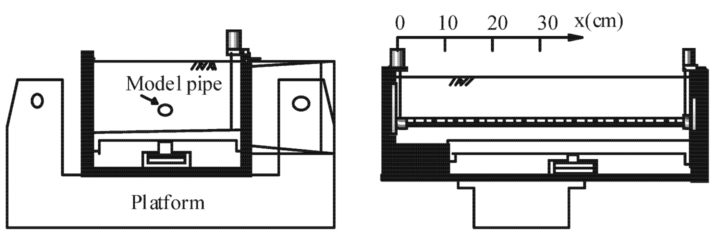


Figure 2. Model configulation.

Table 2. Properties of soils.

Soil	G_s	U_c	ρ_{dmax} (g/cm^3)	ρ_{dmin} (g/cm^3)	ρ_d (g/cm^3)	w (%)	c_d (kPa)	ϕ_d (•)
S0L S0D	2.65	1.8	1.58	1.32	1.43 1.55	0	0 0	37 43
S16L S16M S16D	2.71	70	1.92	1.37	1.50 1.60 1.70	10	9 14 23	38 38 38
S30L S30D	2.67	115	1.86	1.18	1.50 1.70	12	29 45	32 32

Soil	Density	Pipe	H/D
S0	Dense・Loose		2・4
S0	Dense	F	2
S16	Dense・Medium・Loose		2・3・4
S16	Dense・Loose	F	2・4
S30	Dense・Loose		2・4
S30	Dense	F	2

upper and lower surfaces of the inner beam to measure bending strains (ε_m) at 20 locations. Fiber strains (ε) at the surface of the model pipe were obtained by multiplying ε_m by a factor of 4.44 ($=D_m/h$). Distribution of vertical deflection of the model pipe (δ_p) was obtained by integrating ε along the pipe long axis.

Figure 2 shows the model configuration. The model was scaled to 1/30 of the half portion of the prototype ground. The inside length, width and height of a testing container were 590 mm, 300 mm and 205 mm, respectively. The left-side bottom plate of the container, 100 mm long (3 m in prototype), was fixed on the container. The right-side bottom plate, 490 mm long (17.7 m in prototype), was a trapdoor. During the centrifuge flight at 30 g, the trapdoor was lowered at a constant rate by means of a hydraulic cylinder. Both ends of the model pipe were inserted into specially designed end-pieces, mounted on the left and right walls of the container, to generate null rotation allowing vertical displacements. Horizontal displacement of the pipe was constrained at the left end, but not at the right end. Cantilever-type gauges were mounted on the container to measure vertical displacements of the trapdoor and both ends of the pipe. A mirror was also mounted on one side of the container to observe the ground deformation

Table 2 shows properties of three types of sandy soils (S0: silica sand, S16: decomposed granite and S30: silty sand) used in the tests. The numerals following the letter S (Sand) denote fines content; letters, D, M and L, denote dense, medium-dense and loose conditions, respectively. The model grounds were constructed in the lubricated container by pouring for S0-ground and by compaction for both S16- and S30-grounds.

Table 3 shows test conditions. Cover height (H) was varied to be 4, 6 and 8 cm (1.2, 1.8 and 2.4 m in prototype; H/D=2, 3 and 4). The distance between pipe bottom and ground bottom was constant to be 5 cm (1.5 m in prototype) in all tests. A total of 23 tests were conducted.

2.2 *Test results*

In this section, typical measurements from a 3-D centrifuge test with R-pipe, S16D-ground and H/D=2 are represented at prototype scale.

First, it was observed that the settlement of the ground (δ_G) above the left-side fixed bottom plate of the container was close to zero, while δ_G of the ground above the trapdoor was almost identical to the settlement of the trapdoor (s).

Figure 3 shows change in distributions of p_v and p_r, ε, and δ_p due to increase in s. Abscissa x is the distance from the left-end of the pipe; x=3 m corresponds to the boundary between the subsided and non-subsided ground regions. p_v and p_r denote

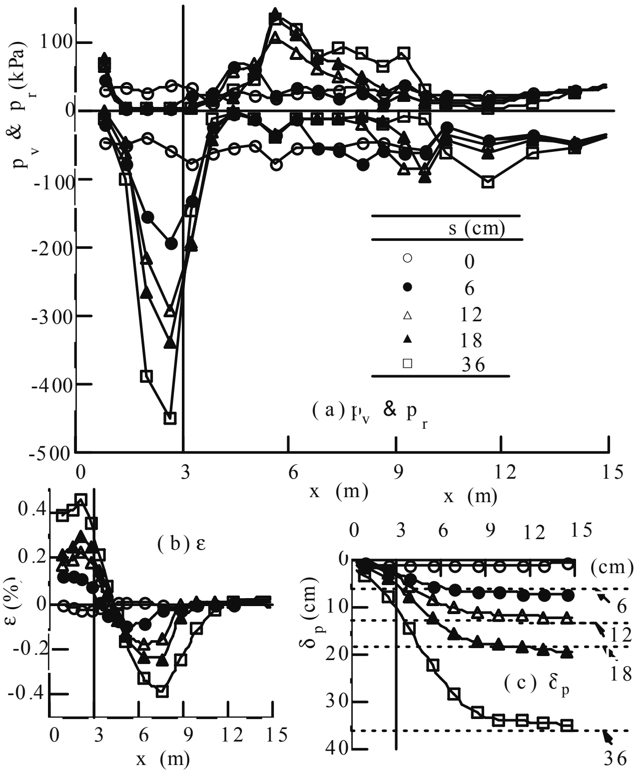


Figure 3. Change in p_v & p_r, ε and δ_p due to increase in s (R-pipe, S16D-ground and H/D=2).

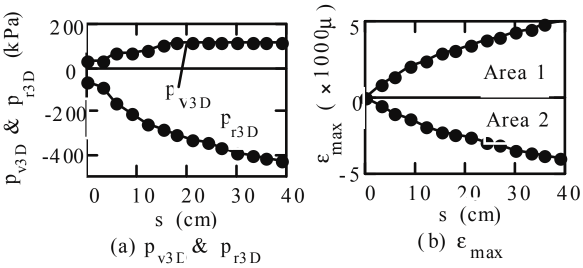


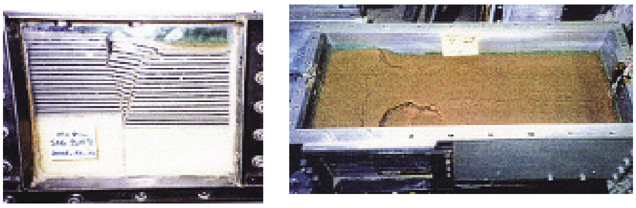
Figure 4. Change in p_{v3D} & p_{r3D} and ε_{max} due to increase in s (R-pipe, S16D-ground and H/D=2).

vertical and vertical reaction earth pressures acting on the upper- and lower-halves of the pipe, respectively. Downward p is counted as positive. Positive ε corresponds to the case when tensile strains produce on the upper surface of the pipe. Measured τ were always negligibly small, and therefore, the data are not presented here. Figure 3 indicated that:

At the left-side area (x<3 m), the pipe settlement (δ_p) was greater than the ground settlement (δ_G). Therefore, the pipe was pushed into the ground (see Fig. 6), resulting in sharp increase in p_r at the vicinity of x=3 m and decrease to almost zero in p_v. At the central area where $\delta_G>\delta_p$ (5-10 m>x≥3 m), however, p_v highly concentrated and p_r decreased to zero. At the right-side area where $\delta_p \geq \delta_G$ (x≥5-10 m), p_r slightly increased, while p_v decreased to almost zero. Here these three areas were named as Area 1, Area 2, and Area 3, respectively. With increase in s, the extent of Area 2 (L) and the peak value of p_v (p_{v3D}) increased, and the location producing p_{v3D} sifted toward right-side, resulting in extension of the area with negative ε.

Figure 4 shows change in the maximum earth pressures (p_{v3D} and p_{r3D}) and the maximum fiber strains (ε_{max}) due to increase in s. The data revealed that the response of pipeline is non-linear. The change in L of Area 2 due to increase in s must have affected this non-linear pipeline response. Furthermore, p_{v3D} shown in Figure 4 were considerably greater (3 times at s=6 cm through 6.5 times at s=36 cm) than the overburden pressure.

Figure 5 shows the ground deformation observed after the test.



(a) Side view (b) Ground surface

Figure 5. Deformation of the S16D-ground observed after the test.

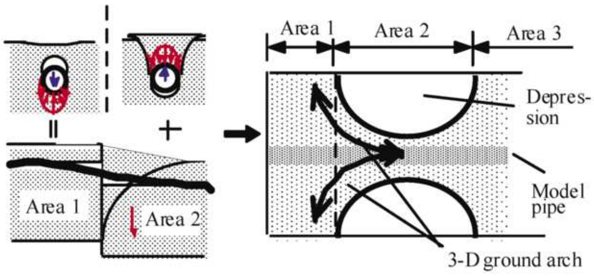


Figure 6. Mechanism of a pair of 3-D ground arch generation.

As shown in Figure 6, two types of slip planes were developed at Area 2. One is in the ground above the pipe, the other on side of the ground. They intersect orthogonally, generating a pair of ground arches between Area 1 and the pipe at Area 2. There was an overlap of the bases of a pair of arches formed in the ground, which may have resulted in the high stress concentration.

Similar tendency was obtained in other tests, but quantitatively p_{v3D} were greater when ground density, H/D and fines content were greater. The effect of pipe flexibility on p_{v3D} was slight. The distribution shape of p_v at Area 2 changed from trapezoid to triangle with increase in the ground density. L of Area 2 were narrower when H/D was greater and pipe flexibility was smaller. It was found, furthermore, that the relative settlement between the pipe and ground ($\delta = \delta_G - \delta_p$) at the locations producing p_{v3D} was close to $0.2\delta_G$ in whole tests.

3 PROPOSITION OF NEW DESIGN METHOD

3.1 *Model and design procedure*

Figure 7 shows a model adopted in the proposed design method, as well as relevant equilibrium equations. In the model, a vertical earth pressure having a parabolic shape is assigned to the upper-half of the pipeline at Area 2; its peak (p_{max}) is assumed to be located at the center of Area 2. Vertical reaction earth pressures acting on the lower-half of the pipeline at both Area 1 and Area 3 are calculated by beam theory on an elastic foundation through $k\delta = k(\delta_G - \delta_p)$, where k is the coefficient of subgrade reaction. Vertical loads (q) at each area are obtained by adding the pipe weight (W_p/D) to these earth pressures.

The design procedure is as follows: First, D, EI and W_p of pipeline, H, ground condition, and δ_G are given as design conditions. If p_{max} and k can be determined as described later, the extent of Area 2 (L) is obtained through iterative computation by using the proposed model to satisfy a condition that the calculated δ_p at the right-end of Area 2 coincides with $\delta_G + W_p/(kD)$.

3.2 *Input constants: p_{max} and k*

The input constants, p_{max} and k, were determined through 2-D centrifuge model tests, in which rigid model pipes were pulled up or pulled down at constant rates in centrifuge flight. Figure 8 shows test setup for the 2-D tests. The rigid model pipes were

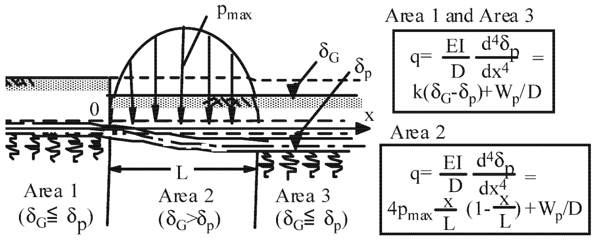


Figure 7. A model adopted in the proposed design method.

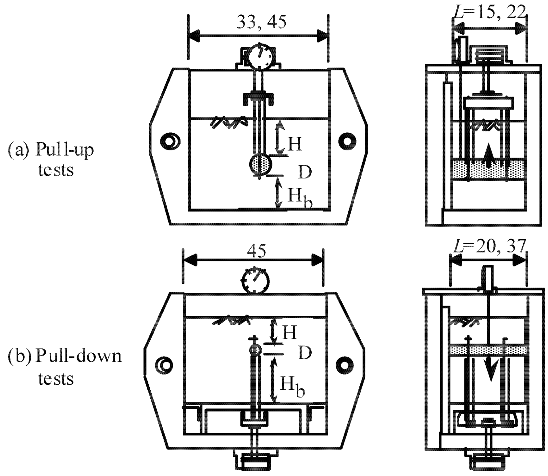


Figure 8. Test setup for the 2-D tests (unit: cm).

Table 4. Conditions of 2-D tests.

Test series	Model pipe D (cm)	Model pipe L (cm)	Centrifugal acceleration (g)	Model H (cm)	Model H_b (cm)	Prototype D (cm)	Prototype H (cm)
Pull-up test	2	22	30	4	4		
	4	22	15	8	8	60	120
	9	15, 22*	6.7	18	10		
Pull-down test	1	20	60	2	4.5		
	2	20, 37**	30	4	9	60	120
	4	20, 37**	15	8	18		

*S30D-ground only. **Dense ground only.

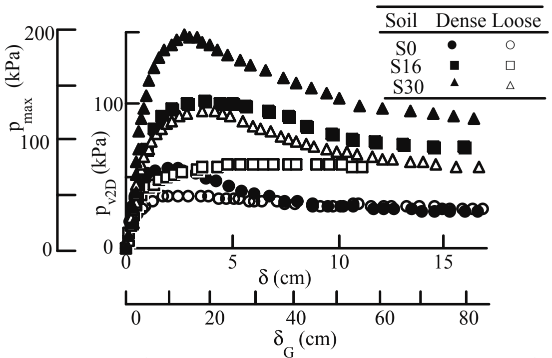


Figure 9. $p_{v2D} \sim \delta$ curves obtained in the pull-up tests and p_{max}-δ_G curves for design usage.

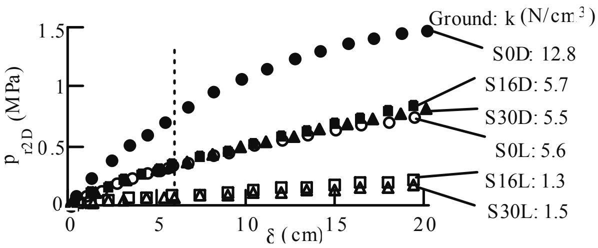


Figure 10. $p_{r2D} \sim \delta$ curves obtained in the pull-down tests and k values at δ=6cm for design usage.

buried in the six types of grounds that were same as those used in the 3-D tests (Table 2), except S16M-ground was not used. H/D was constant and equal to 2. Table 4 shows test conditions. Different D of pipe, H, and centrifugal accelerations were combined to generate an identical prototype with D=60 cm and H= 120 cm. A total of thirty-six tests were conducted.

The 2-D tests generated almost identical p_{v2D}-δ and p_{r2D}-δ curves for the same ground conditions, revealing that similarity law was fully satisfied. Here, p_{v2D} and p_{r2D} are vertical earth pressures acting on the upper- and lower-halves of the pipe, and δ is upward or downward displacement of the pipe (=relative settlement between the pipe and ground).

Figure 9 shows p_{v2D}-δ curves obtained in the pull-up tests for 6 types of grounds. When comparing these p_{v2D}-δ curves with p_{v3D}-δ (=$0.2\delta_G$) curves obtained in the 3-D tests at the same δ, it was found that p_{v3D} were always approximately 1.3 times greater than p_{v2D}, that is, $\alpha=p_{v3D}/p_{v2D}=1.3$. Therefore, p_{max}-δ_G curves to be used for design can be obtained, as shown by auxiliary axes in Figure 9, by multiplying ordinate and abscissa of p_{v2D}-δ curves by 1.3 (=α) and 5(=δ_G/δ), respectively.

Figure 10 shows p_{r2D}-δ curves obtained in the pull-down tests for 6 types of grounds. The curves are approximately linear, except for S0D-ground. Here, the values of k to be used for design were determined as the inclinations of these curves at δ=0.1D=6 cm, whose values are shown in the figure. These k values correspond to almost their upper bounds.

4 COMPARISON OF PREDICTION AND 3-D TESTS

Predicted results according to the proposed method were compared with the ten 3-D model tests with D=60 cm and H=120 cm. The values of p_{max} and k were determined from Figures 9 and 10. The boundary conditions in the calculation were adjusted to those of the tests. It was confirmed that even if the extents of Area 1 and Area 3 were extended to be infinite, the calculated results were almost the same as those presented here.

Typical examples of the comparison are shown in Figure 11 and Figure 12. In these figures, the marks and lines denote test and predicted results, respectively. Δp denote $|p_v|-|p_r|$ for the tests and $q-W_p/D$ for the prediction; in the latter, [illegible] is necessary for comparing with the test results, because the measured p_v did not involve the pipe weight. The predicted results conformed well to the test results without any exception, resulting in reasonable explanation for both the non-linear change in the pipeline response due to increase in differential ground settlement and the effects of the factors on the pipeline response.

5 CONCLUSIONS

The 3-D centrifuge model tests clarified non-linear change in response of pipelines due to increase in differential ground settlement. A new rational design method that can predict actual response of pipelines quite well was proposed on the basis of findings from the tests. Input constants, p_{max} and k, for different cover heights and pipe diameters required for design will be provided as a design tool in the near future.

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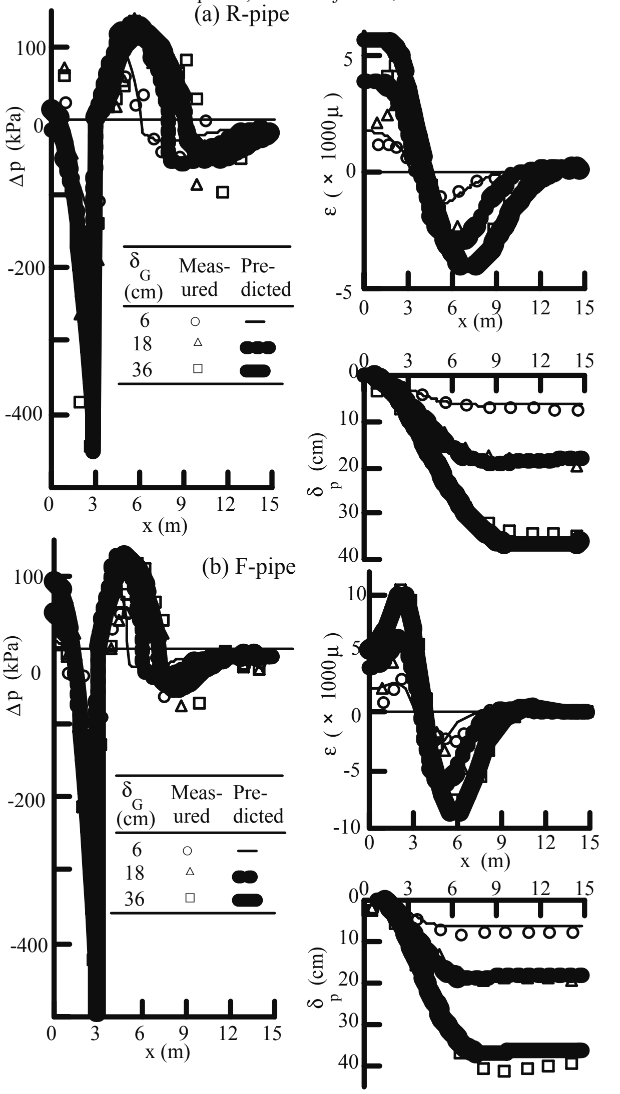

Figure 11. Comparison between test and prediction for different δ_G and pipe flexibilities (S16D-ground).

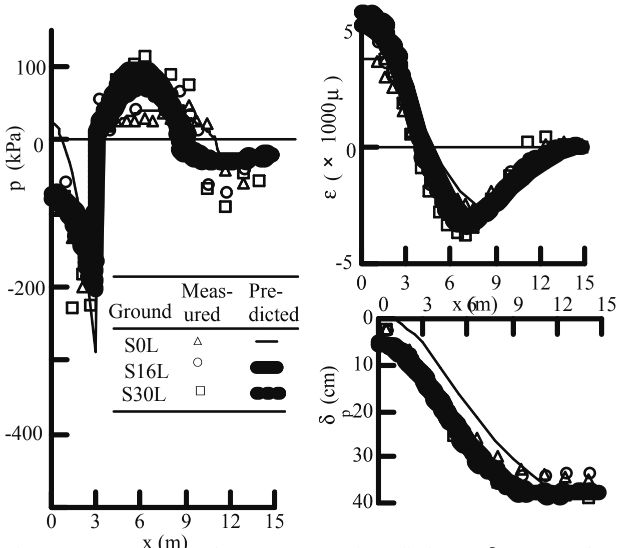

Figure 12. Comparison between test and prediction at δ_G=36 cm for different loose grounds (R-pipe).