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Anti-Seismic Reinforcement of Pipelines in a Liquefied Ground

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SYNOPSIS: An anti-seismic structural-reinforcemental method for buried pipelines is presented and anlaytically investigated on the effectiveness for lateral flow of liquefied grounds during earthquakes. The proposed method of the reinforcement is to fix main pipelines with expansion joints to parallel auxiliary continuous pipes using iron-plates. Stiffness of liquefied soils around pipes is represented as a coefficient of subgrade reaction between liquefied sand deposits and pipes, based on the experimental results. Analysis of the pipeline-soil spring systems is conducted using the modified transfer matrix method.

Computations are performed with respect to the displacement, strain, stress, joint expnasion, and rotational angle of joint of pipelines, based on the soil-pipe interaction. Furthermore brief comparisons between the proposed method and other works are also made.

INTRODUCTION

Liquefaction occurs during relatively large earthquakes and gives serious damages to urban areas, especially to lifeline facilities. Since the mobility of soil is very high during liquefaction, secondary disasters such as global lateral flows of soil or landslides take place and cause serious damages to pipelines. A report(Hamada,1986) says that the maximum permanent displacements of the ground for the 1964 Niigata Earthquake was 8.8 m, and for the 1983 Nihonkai-Chubu Earthquake 5.0 m by the interpretation of photos taken before and after the earthquakes.

Since the 1964 Niigata earthquake, protective methods or works for liquefaction have been developed and executed, in which mostly the sand-compaction piles are driven to increase the density of sand in Japan. However few of those works have been tested by earthquakes to the effectiveness and therefore more tests and observations on liquefaction would be required in future.

As the structural strengthening of pipes is concerned, anti-seismic joints for ductile cast iron pipes which allow much greater deformation of joints than usual expansion joints were developed and have replaced the old-type joints. However investigation after earthquakes shows that even this anti-seismic joints are not enough for resisting the huge ground flow due to liquefaction.

This study, as an auxiliary method for soil improvement, presents a method to increase the resistance of pipelines for static lateral loads, by fixing main pipelines with expansion joints to parallel auxiliary continuous pipes using iron tie-plates. The model of proposed stiffened pipes will be analyzed and compared with other anti-liquefaction methods.

MODELLING OF REINFORCED BURIED PIPELINES

The concept of proposed reinforced pipelines is shown in Fig. 1, which are expected

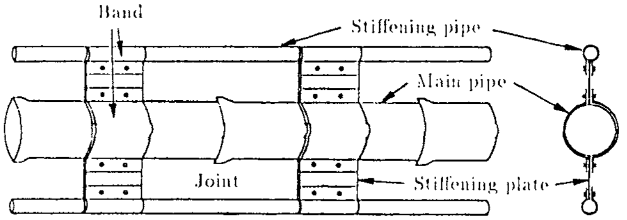


Fig.1 Geometry of a Reinforced Pipeline (Plan view)

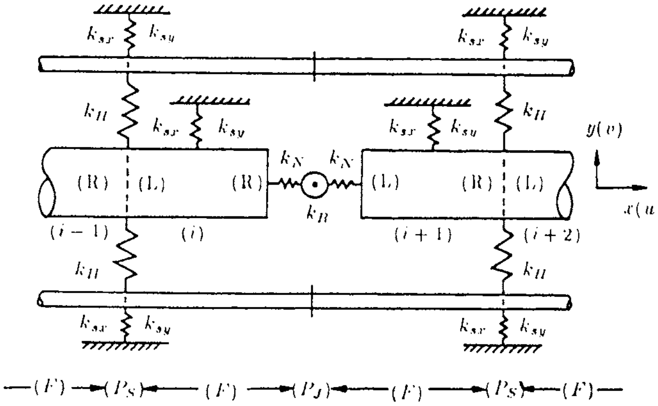


Fig.2 Modelling of a Reinforced Pipe (Plan view)

to resist the lateral flow of soil as a system that the main pipe(:central pipe in the diagram) and the both-sided continuous stiffening pipes cooperate through stiffening plates. Based on the results(Takada, 1988/ Akiyoshi, 1990) of the interactive experiments between liquefied sand deposits and pipes, stiffness of liquefied soils around the pipes can be represented as a coefficient of subgrade reaction. Thus the reinforced pipelines are modelled as the pipeline-soil spring system as shown in Fig. 2. In the diagram, pipes are connected not only by expandable joint of the spring constant k_T and rotational joint of the spring constant k_R but also supported by the soil springs k_{sx}(:axial) or k_{sy}(:lateral). In the diagram k is the spring constant of the stiffening plates.

ANALYTICAL PROCEDURES

In the analysis following assumptions are used:
(1) Pipelines are elastic until final deformations.
(2) Axial and lateral movements are independent of each other.
(3) Inertia and damping forces are neglected.

Based on the assumptions above, the equations for axial and lateral(:bending) equilibrium are separately written as follows:

a) Equation of a pipe in the axial direction:

$$-EA\frac{d^2u}{dx^2} + k_{sx} \cdot u = k_{sx} \cdot u_{sx} \tag{1}$$

b) Equation of a pipe in the lateral direction:

$$EI\frac{d^4v}{dx^4} + k_{sy} \cdot v = k_{sy} \cdot v_{sy} \tag{2}$$

where $E, I, A =$ Elastic constant, geometrical moment of inertia and area, respectively, of the pipe, $k_{sx}, k_{sy} =$ spring constants of the soil per unit length of the pipe, respectively, u, v = axial and lateral displacements of the pipe, respectively, $u_{sx}, v_{sy} =$ axial and lateral displacements of the soil, respectively, P = Body force acting laterally to the pipe such as buoyance.

Now let the state vector V be

$$V' = [y', z'] \tag{3}$$

where $y' = [u, v, \psi]$, $z' = [N, M, Q]$, and $\psi, N, M, Q =$ deflection angle, axial force, bending moment and shear force of the pipe, respectively.

Eqs. (1) and (2) can be rewritten as

$$\frac{dV}{dx} = AV + f(x) \tag{4}$$

where

$$A = \begin{bmatrix} 0 & 0 & 0 & -1/E_cA_c & 0 & 0 \\ 0 & 0 & -1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -1/E_cI_c & 0 \\ -k_{sx} & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & -k_{sy} & 0 & 0 & 0 & 0 \end{bmatrix} \quad f(x) = \begin{bmatrix} 0 \\ 0 \\ q(x) \\ 0 \\ 0 \\ p(x) \end{bmatrix}$$

and $q(x) = k_{sx} \cdot u_{sx}$=distributed load acting in the axial direction, $p(x)$ =distrbuted load acting in the lateral direction.

[Field transfer]

Using a refined transfer matrix method(Nakamura, 1979), the state vectors $V_{i,L}$ and $V_{i,R}$ will satisfy the following equation;

$$[\ \overrightarrow{a},\ \overrightarrow{b}\ ]_{i,L}\, V_{i,L} = \overrightarrow{c}_{i,L} \tag{5}$$

$$[\ \overrightarrow{a},\ \overrightarrow{b}\ ]_{i,R}\, V_{i,R} = \overrightarrow{c}_{i,R} \tag{6}$$

where $V_{i,L}, V_{i,R} =$ state vectors at the left and right ends of the i-th pipe element, $\overrightarrow{a}$, $\overrightarrow{b}$, $\overrightarrow{c}$=coefficient square matrices which denote the transfer of "left to right".

Let F_i be the "left to right" field tansfer matrix of 3 parallel stiffened pipes system in Fig. 2, which will follow the field transfer matrix for a single pipe obtained from eq. (4). Then $V_{i,R}$ and $V_{i,L}$ will be related to each other by:

$$V_{i,R} = F_i\, V_{i,L} + g_{i,L}, \qquad F_i = \exp(Al) \tag{7}$$

Substitution of eq. (7) into eq. (6) will lead to the following relations of the field transfer;

$$[\ \overrightarrow{a},\ \overrightarrow{b}\ ]_{i,R} = [\ \overrightarrow{a},\ \overrightarrow{b}\ ]_{i,L} \cdot F_i^{-1} \tag{8}$$

$$\overrightarrow{c}_{i,R} = \overrightarrow{c}_{i,L} + [\ \overrightarrow{a},\ \overrightarrow{b}\ ]_{i,L} \cdot F_i^{-1} g_{i,L} \tag{9}$$

[Point transfer]

The state vectors $V_{i,R}$, $V_{i+1,L}$ at the point(joint) between the pipe elements(i) and (i+1) can be written as

$$V_{i+1,L} = \overrightarrow{P}\, V_{i,R} \tag{10}$$

$$V_{i,R} = \overleftarrow{P}\, V_{i+1,L} \tag{11}$$

where $\overrightarrow{P}$, $\overleftarrow{P}$ = point transfer matrices correspondingt to "left to right" and "right to left" transfer, respectively.

Substituting eq. (11) into eq. (6) leads to

$$[\ \overrightarrow{a},\ \overrightarrow{b}\ ]_{i+1,L} = [\ \overrightarrow{a},\ \overrightarrow{b}\ ]_{i,R}\, P_k\ ,\ (k = J \text{ or } S) \tag{12}$$

$$c_{i+1,L} = c_{i,R} \tag{13}$$

For the case for transfer of $\overrightarrow{a}$, $\overrightarrow{b}$, $\overrightarrow{c}$ from the left side of the point(joint) to the right side, the point transfer matrix P becomes

$$\overrightarrow{P_J} = \begin{bmatrix} \mathrm{I} & & & & & \\ 0 & \mathrm{I} & & & \overrightarrow{P_2} & \\ 0 & & \mathrm{I} & & & \\ 0 & & & \mathrm{I} & & \\ 0 & & & & \mathrm{I} & \\ 0 & & & & & \mathrm{I} \end{bmatrix}, \quad \overrightarrow{P_2} = \begin{bmatrix} -1/k_T & & \\ 0 & 0 & 0 \\ 0 & -1/k_R & 0 \end{bmatrix}$$

$$P = \begin{bmatrix} \mathrm{I} & & & & & \\ 0 & \mathrm{I} & & & \overrightarrow{P_2} & \\ 0 & & \mathrm{I} & & & \\ K_1 & K_2 & & \mathrm{I} & & \\ K_3 & K_4 & K_5 & & \mathrm{I} & \\ 0 & K_6 & K_7 & & & \mathrm{I} \end{bmatrix}$$

where $K_1, \cdots, K_7$ = =stiffness matrix(3x3) of the stiffening plates.

Using the same procedures, transfering of the coefficients $\overleftarrow{a}$, $\overleftarrow{b}$, $\overleftarrow{c}$ from right to left boundaries yields

$$[\ \overleftarrow{a},\ \overleftarrow{b}\ ]_{i,L}\, V_{i,L} = \overleftarrow{c}_{i,L} \tag{14}$$

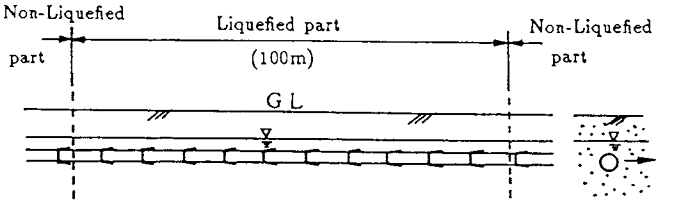
Therefore the state vector $V_{i,L}$ will be obtained by solving eqs. (5) and (14).

SOIL- PIPELINE MODELS FOR ANALYSIS

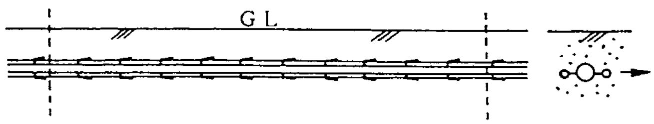
In this analytical study the effectiveness of the proposed pipeline model (:reinforced pipeline) which is sohwn in Fig. 3 [b] as Case 2 is compared with the other anti-liquefaction methods (:Cases 1, 3 and 4).

Table 1 Standard Dimensions of Pipelines

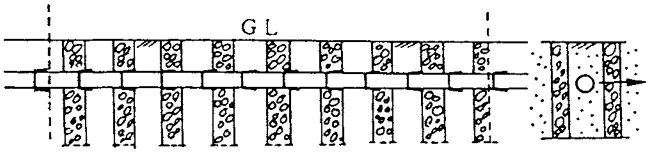
	ϕ_0 (mm)	ϕ (mm)	t (mm)	E (kgf/cm^2)
Main pipe	500	528	0.5	1.6×10^6
Stiffening pipe	100	118	7.5	1.6×10^6
	h (mm)	w (mm)	t (mm)	E (kgf/cm^2)
Stiffening plate	500	500	10	1.6×10^6



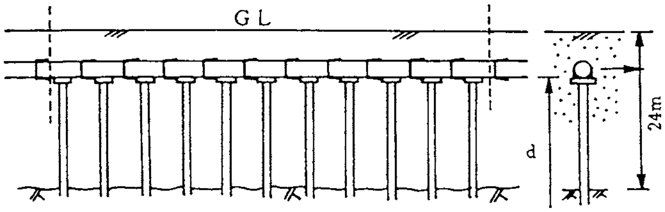
[a] (Case1): Single Pipe



[b] (Case2): Reinforced Pipe



[c] (Case3): Gravel-Drained



[d] (Case4): Pile-Supported

Fig.3 Anti-Liquefaction Models for Analysis

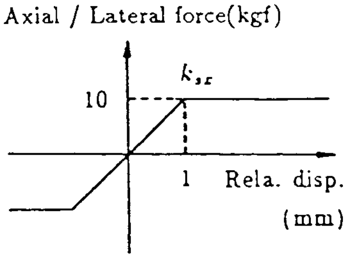


Fig.4 Stiffness of Soil; k_{sx}, k_{sy}

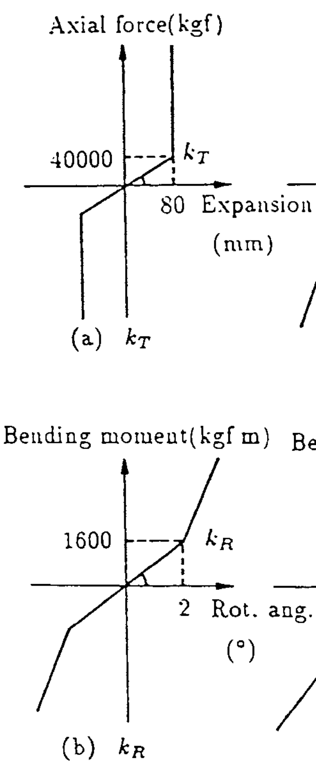


Fig.5 Stiffness of Joints(S-type)

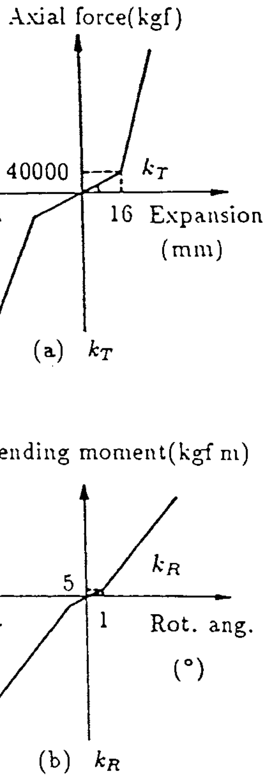


Fig.6 Stiffness of Joints(GM-type)

[Soil conditions] The liquefied region of soil is restricted to 100 m as shown in Fig. 3[a] and laterally flown to 2 m (vertical to the paper face), but the displacements of both sides of non-liquefaction area are very small.

[Pipes] As shown in Table 1, standard dimensions of pipelines used for every case are assumed to be ductile cast iron pipes of diameters 500 mm and 100 mm, for the main pipe and the stiffening pipe,respectively, and the stiffening plate is of steel 500 mm x 500 mm x 10 mm(:thickness). Pipes are buried horizontally just beneath the ground surface.

[Stiffness of soils and joints] Based on the results of interactive experiments between liquefied sand deposits and pipes(Takada, 1988/ Akiyoshi, 1990), stiffness of liquefied soils can be represented as a non-linear coefficient of subgrade reaction of 1 % of the stiffness of the non-liquefied soil, as shown in Fig. 4.

Joint stiffness is characterized as non-linear axial springs k_T and rotational ones k_R where the stiffnesses are hard for S-type(:Anti-seismic joint for general use) and soft for GM-type(:joint for gas line use), respectively, as shown in Figs. 5 and 6.

ANALYTICAL RESULTS AND CONSIDERATIONS

[Reinforced pipe vs. single pipe] Fig. 7 is the diagrams of the response of the pipes with GM-type joints to 2 m lateral displacement of the liquefied soil in which the dotted and solid lines show the responses of Case 1(:single pipe) and Case 2(:reinforced pipe), respectively.

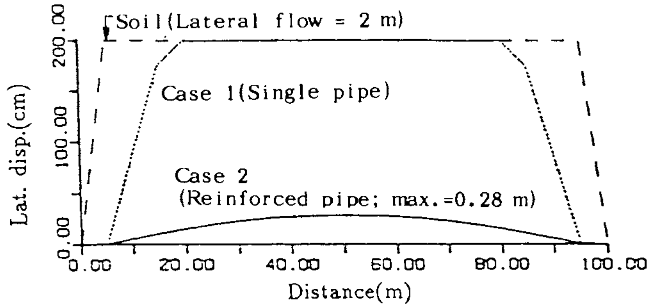
Fig. 7(a) shows that the lateral displacement of 0.28 m of the reinforced(stiffened) pipe is far less than the displacement of 2 m of the single pipe. Thus reinforcement effect is very remarkable for reducing the lateral displacement of the pipes for the lateral flow of the liquefied soil.

So it is noted that the pipelines with such soft joints as GM-type cannot resist the flow of liquefied soil and thus are subject to heavy deformation at the liquefied-nonliquefied (L-NL) boundaries.

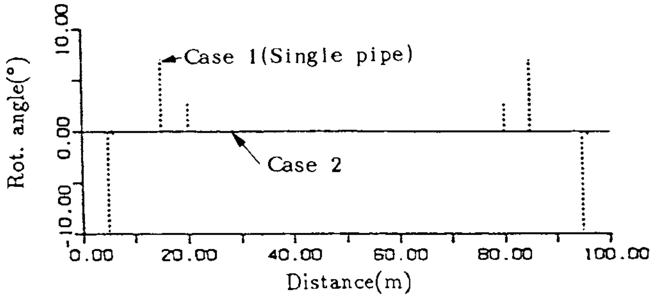
It follows from the diagram (a) that the rotational angle (:Fig. 7(b)) of the single pipe reaches 10°which is far above the allowable angle of 5°, and joint expansion (:Fig. 7(c)) of 8 cm which also exceeds the absorbing ability of 5 cm. However the responses of the reinforced pipes are very small.

Maximum bending stress naturally occurs closely to L-NL boundaries(:diagram(d)). Maximum bending stress(:120 kgf/cm^2) of single pipes seems to be much smaller than that(:800 kgf/cm^2) of reinforced main pipes. But this does not mean that the bending resistance of a single pipe is greater than that of the reinforced main pipe, because adjacent joints in the single pipeline have already yeilded.

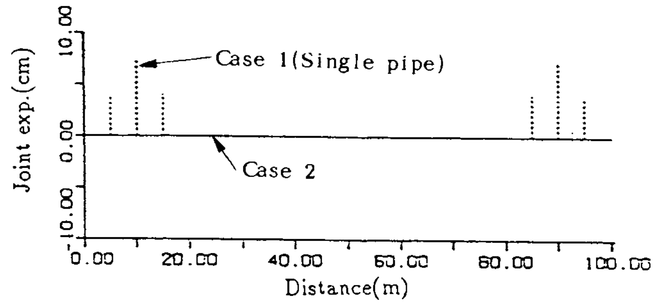
Thus for the 2 m lateral external force of liquefied soil, single pipelines completely break and reinforced pipelines are generally safe. It is clear that the stress of the pipes and stiffening plates can be reduced by adjusting the dimensions.



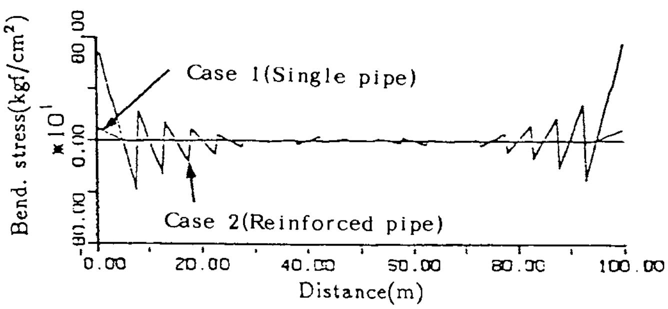
(a)Lateral Disp. of Soil and Main Pipe



(b)Rotational Angle of Joint

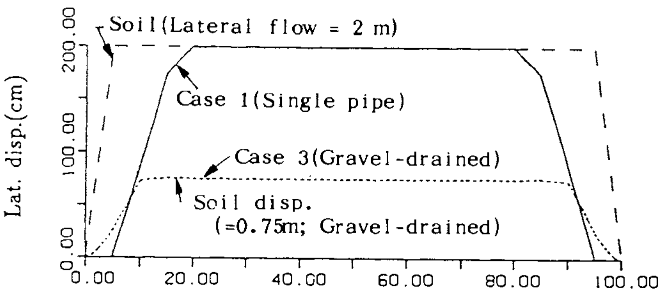


(c)Joint Expansion

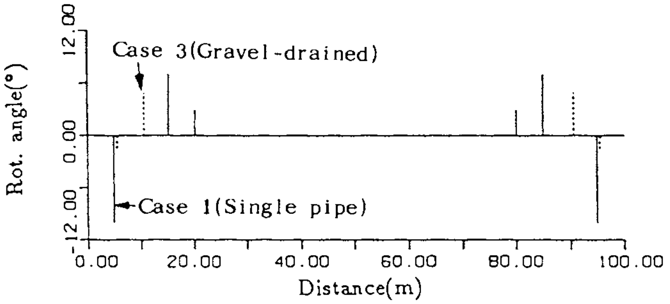


(d)Bending Stress of Main Pipe

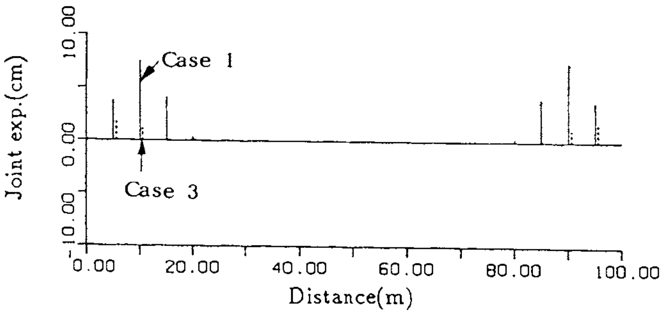
Fig.7 Response of Pipes for Lateral Displacement of Soil
[Cases 1 and 2; Soil disp.=2m, GM-type joint]



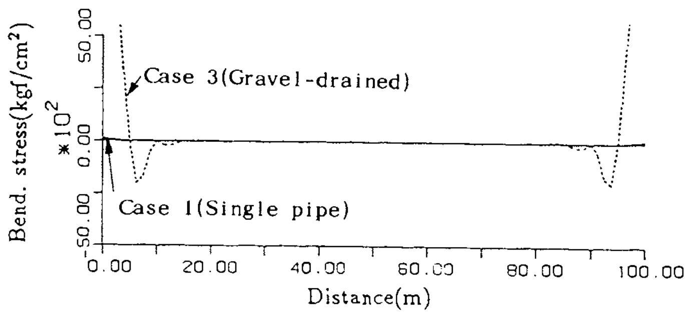
(a)Lateral Disp. of Soil and Main Pipe



(b)Rotational Angle of Joint

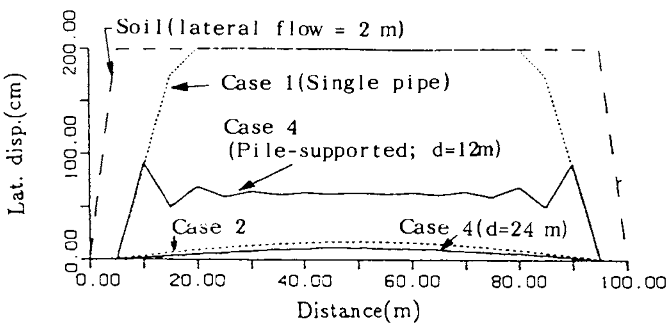


(c)Joint Expansion

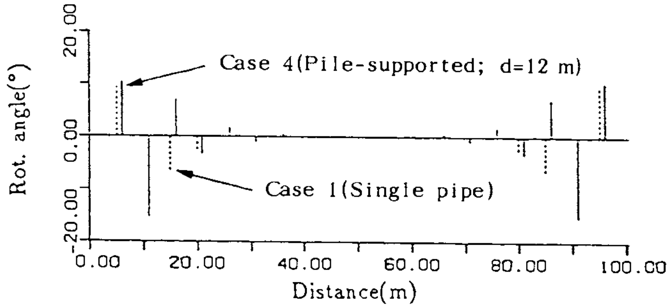


(d)Bending Stress of Main Pipe

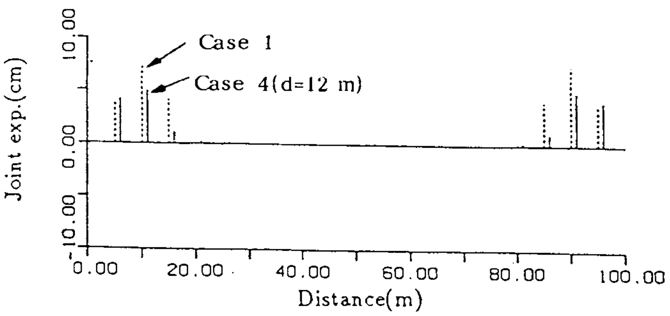
Fig. 8 Response of Pipes for Lateral Displacement of Soil [Cases 1 and 3; Soil disp.=.75m, CM-type joint]



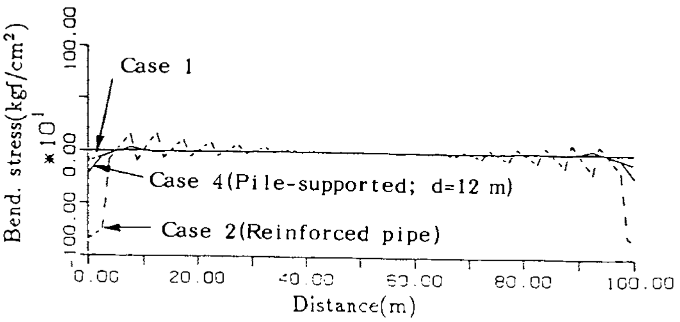
(a)Lateral Disp. of Soil and Main Pipe



(b)Rotational Angle of Joint



(c)Joint Expansion



(d)Bending Stress of Main Pipe

Fig. 9 Response of Pipes for Lateral Displacement of Soil [Cases 1, 2 and 3; Soil disp.=2 m, CM-type joint]

[Gravel-draining vs. single pipe] Now let us consider the gravel-drained ground as one of the anti-liquefaction methods(:Fig. 8). Since gravel piles lower the excess pore pressure around very close region and depress the generation of liquefaction, stiffness of the soil still survives For a tilted ground with the slope of 3 %, the lateral displacement of the soil was set to 2 m for uniformly liquefied ground and computed to 75 cm for the gravel-drained case. From Fig. 8(a), the stiffness of the single pipe cannot resist the deformation of the soil and finally causes perfect failure by bending moment at L-NL boundary(:lowest diagram(d)).

[Pile-supporting vs. single and stiffened pipes] Effectiveness of another anti-liquefaction method that supports a new pipeline by vertical piles(the diameter=319 mm, thickness=7 mm) as shown in Fig. 3(d)(: Case 4) is compared both with the reinforced pipe method(:Case 2) and single pipe method(:Case 1) in Fig. 9. In this case the vertical profile of the ground where the thickness of the surface layer=24 m for the computation is modelled (Daibuzono, 1988) for a district of Kawagishi-cho, Niigata city, Japan and the stiffness of liquefied soils around the pipes represented as a coefficient k of subgrade reaction is calculated by the experimental relation for piles(Matumoto, 1987):

$$k\,(\mathrm{kgf/cm^3}) \cong 0.13\sigma'_v\,(\mathrm{kgf/cm^2})$$

where σ'_v is the remaining effective stress of the liquefied soils which will be decided based on the seismic response of the finite elemental model of water-saturated soil.

Fig. 9(a) shows that floating piles(:embeddment d=12 m) are not effective to resist and control the displacement of ground surface. However the effectiveness of bearing piles (:d=24 m) are comparable with the proposed method. Therefore shallow embeddment of piles gives almost same rotational angle of joints (:diagram(b)) and joint expansion (:diagram(c)) as the case of the single pipe which is far over the allowable values of expansion joints. However deep embeddment of piles has similarly high effectiveness of anti-liquefaction method on support of pipelines with the reinforced method.

CONCLUSION

A simple structural-reinforcing method to protect buried pipes for the lateral flow of liquefied without soil improvement ground was presented as an auxiliary method , and the effectiveness of the proposed method was analyzed comparing with other anti-liquefaction methods.

Usual pipe-expansion joint or even anti-seismic joint supply systems are not so effective to resist and prevent such large displcaements as lateral flow of liquefied ground that the stress of pipes concentrates closely at the liquefied-nonliquefied boundary and exceeds the allowable capacities. However the proposed method reduces not only the total deformation of pipes but also the stress concentration at the boundary. Further it might be rather economical that used iron pipes are avbailable as stiffening pipes in proposed reinforced system.

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