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Stiffening effect of anti-liquefaction techniques for buried pipes

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ABSTRACT: An anti-liquefaction method that pipelines are fixed parallel to auxiliary continuous pipes using iron tie-plates is proposed for preventing large deformations for lateral flow of liquefied grounds during earthquakes. Pipeline-spring systems which are characterized by coefficients of subgrade reaction are analyzed based on the theory of "a beam on the elastic foundation" and transfer matrix method. The permanent displacements of pipelines, rotational angles of joints, and stresses of pipelines are investigated and compared with other several anti-liquefaction methods by soil-improving or structural-stiffening.

1 INTRODUCTION

Many severe damages of buried pipelines during earthquakes have been caused by large deformation or flow of soil layers induced by liquefaction. It was reported that the maximum permanent displacements of the ground amounted 8.8 m for the 1964 Niigata Earthquake and 5.0 m for 1983 Nihonkai-Chubu Earthquake, respectively, by the interpretation of aerial photos taken before and after the earthquakes (Hamada 1986). It was also cleared that large displacement of liquefied soil was mostly induced in the sandy soil with dipping surface.

Since the 1964 Niigata Earthquake, many protective methods or works for liquefaction have been developed and executed, but the effectiveness of those works have not been tested in practice by earthquakes and therefore more tests and observations on liquefaction would be required in future. Concerning the structural strengthening of pipes, anti-seismic joints for ductile cast iron pipes which allow great deformation of joints were developed and have replaced the old-type joints. However investigation after earthquakes shows that even those anti-seismic joints are not enough for resisting the huge ground flow due to liquefaction.

This study aims to investigate and compare the effects of anti-liquefaction techniques for buried pipelines which include structural reinforcing method. The proposed method is to increase the resistance of pipelines for static lateral loads of liquefied soils, by fixing main pipelines with expansion joints to parallel auxiliary continuous pipes using iron tie-plates.

2 ANALYTICAL METHOD OF A REINFORCED PIPELINE

Fig.1 shows the concept of a proposed reinforced pipeline which resists the lateral flow of soil as a system that the main pipe (:central pipe) and the both-sided continuous stiffening pipes cooperate through stiffening plates. The stiffness of liquefied soils around the pipes are replaced with a coefficient of subgrade reaction. Thus the reinforced pipeline is modelled as the pipeline-soil spring system as shown in Fig.2. Main pipe segments are connected by flexible joints of the axial spring constant k_T and rotational one k_R, and every pipe is supported by the soil spring k_{sx} (:axial) and k_{sy} (:lateral). In the diagram k_H represents the spring constant of the stiffening plates.

The effectiveness of the proposed method and another several anti-liquefaction methods is investigated based on the response analysis of buried pipelines. The assumptions used in the analysis are as follows:

(1) Stiffnesses of pipe and soil are bi-linear elastic.
(2) Axial and lateral movements are independent.
(3) Inertia and damping forces are neglected.

Based on the above assumptions, the equations for

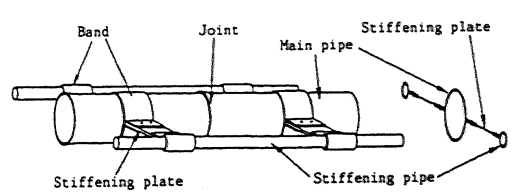

Fig.1 Geometry of a Reinforced Pipeline

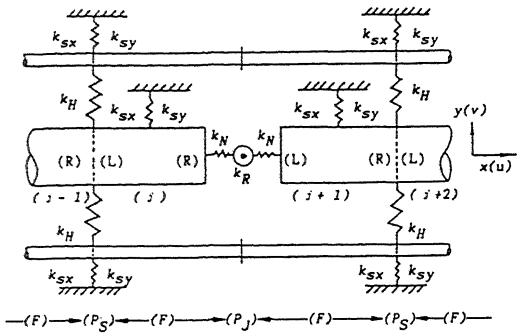

Fig.2 Modelling of a Reinforced Pipe (Plan view)

axial and lateral (:bending) equilibrium are separately written as follows:

$$-EA\frac{d^2u}{dx^2} + k_{sx}\cdot u = k_{sx}\cdot u_{sx} \quad \text{(:axial)} \tag{1}$$

$$EI\frac{d^4v}{dx^4} + k_{sy}\cdot v = k_{sy}\cdot v_{sy} + P \quad \text{(:lateral)} \tag{2}$$

where E, I, A = Elastic constant, geometrical moment of inertia and area, respectively, of the pipe, 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.

These equations can be solved by using a refined transfer matrix method (Nakamura, 1979), but the procedure of the analysis is not shown here [It's shown in Akiyoshi 1989 and Daibuzono 1988].

3 SOIL-PIPELINE MODELS FOR ANALYSIS

It is assumed that the locally liquefied soil block of the width of 100 m are laterally flown by 2 m (vertical to the paper face) as shown in Fig.3 [a], but displacements of both sides of non-liquefaction area are very small. It is also assumed that main pipes are DCI ones of the standard length of 5 m and stiffening pipes are continuous such as welded or flange-type joints. Standard dimensions (:DCI pipe) used for every case are shown in Table 1, the main pipe, the stiffening pipe and the stiffening plate (:steel). Pipes are buried horizontally and closely to the ground surface.

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 bi-linear coefficient of subgrade reaction of 1 % of the stiffness of the non-liquefied soil, as shown in Fig.4.

Joint stiffness of pipes is characterized as bi-linear axial springs k_T and rotational ones k_R for S-type (:Anti-seismic joint for general use) and for GM-

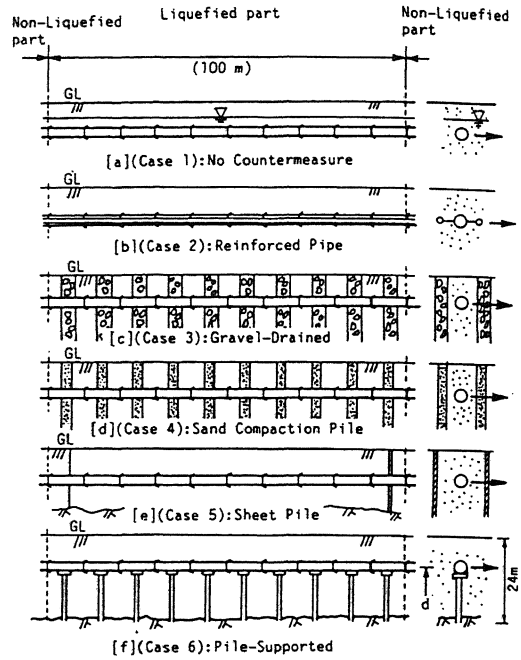

Fig.3 Anti-Liquefaction Models for Analysis

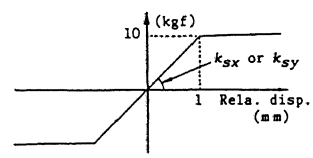

Fig.4 Stiffness of Soil; k_{sx}, k_{sy}

Table 1 Standard Dimensions of Pipelines

	ϕ_0 (mm)	ϕ (mm)	t (mm)	E (kgf/mm²)
Main pipe	500	528	0.5	1.6×10^4
Stiffening pipe	100	118	7.5	1.6×10^4

	h (mm)	w (mm)	t (mm)	E (kgf/mm²)
Stiffening plate	500	500	10	1.6×10^4

type (:joint for gas line use), respectively, as shown in Figs.5 and 6.

4 ANTI-LIQUEFACTION MODELS FOR ANALYSIS

Existing anti-liquefaction techniques for lateral flow of soil can be classified into two groups (Yasuda 1988), in which one is to prevent occurrence of liquefaction and another is to prevent soil flow under liquefaction. Procedures of former groups are executed frequently by sand-compaction pile works for increasing density of soils, especially in Japan (Tanaka, 1991). Procedures of latter groups are practiced by the sheet piles,

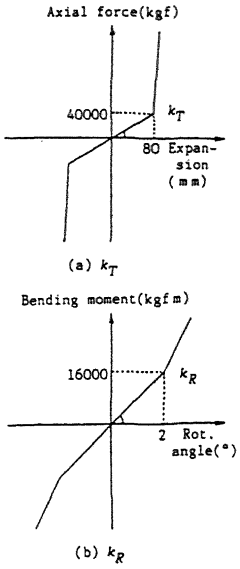

Fig.5 Stiffness of Joints(S-type)

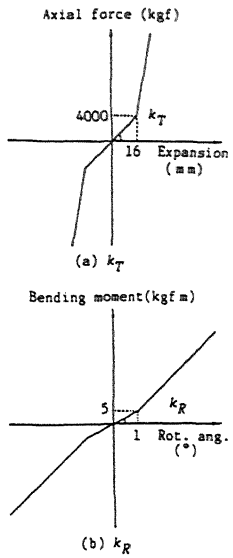

Fig.6 Stiffness of Joints(GM-type)

the diaphragm walls or the geotextiles for resisting ground flow.

In this study we deal with the gravel-drained (Fig.3 [c]) and the sand-compaction pile (Fig.3[d]) methods as preventive methods for liquefaction, and the sheet piles (Fig.3[e]) as another protective techniques for sand flow. Two parameters of lateral displacements and spring constants of soils are carefully and properly decided to represent the soil stiffness of these three methods since they are key parameters in this study. Fig.7 shows the examples of the lateral flow of sandy soil layer during liquefaction process by the model experiment which is followed well by FEM analysis (Akiyoshi 1991). Thus based on the results by above approach, another experiments and analyses [Akiyoshi 1991, Shirinashihama 1991, Tanaka 1991], these two parameters are decided as denoted later in computational results.

The pile-supporting method (Fig.3[f]) is a typical example of the structural improvemental methods to increase the bending resistance of pipes. In this paper another anti-liquefaction technique of reinforcing pipes is proposed and compared with above other preventive methods.

5 COMPUTATIONAL RESULTS AND CONSIDERATIONS

5.1 Reinforced pipe vs. no countermeasure

Fig.8 shows the responses of the pipes with GM-type joints for lateral displacement of the liquefied soil, in which the dotted and solid lines denote the responses

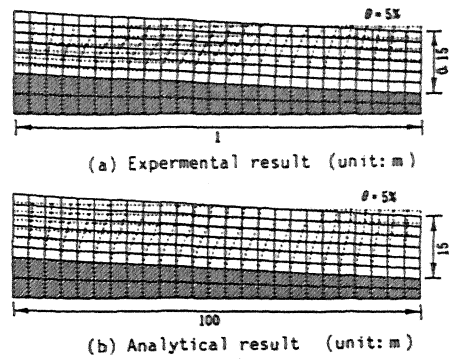

Fig.7 Examples of Lateral Flow by the experiment and the analysis

of Case 1 (:no countermeasure) and Case 2 (:reinforced pipe), respectively, and the broken line the soil displacement of 2 m.

The lateral displacement of 0.28 m of the reinforced (stiffened) pipe is far less than that of 2m of the single pipe which follows the movement of the soil. This means that reinforcement is very effective for reducing the lateral displacement of the pipes for the lateral flow of the liquefied soil.

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

Maximum bending stress naturally occurs closely to L(:Liquefied)-NL(:Non-Liquefied) boundaries (:diagram(d)). Maximum bending stress (:120 kgf/cm^2 (1.176×10^7 Pa)) of single pipes seems to be much smaller than that (:800 kgf/cm^2 (7.84×10^7 Pa)) 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 pipe have already yielded.

Thus for the 2 m lateral displacement of the liquefied soil, single pipes will completely break and reinforced pipes survive.

5.2 Gravel-draining vs. no countermeasure

Now consider the gravel-drained ground as one of the anti-liquefaction methods (:Fig.9). Since gravel piles lower the excess pore water pressure of the circumferences and depress the generation of liquefaction, stiffness of the soil still survives. For a tilted ground with the slope of 5%, the expected lateral displacement of the ground surface can be computed to be 0.75m for the gravel drained case (Akiyoshi 1991), whereas instead of the surface displacement of 2m of no-countermeasured ground. From Fig.9(a), no coun-

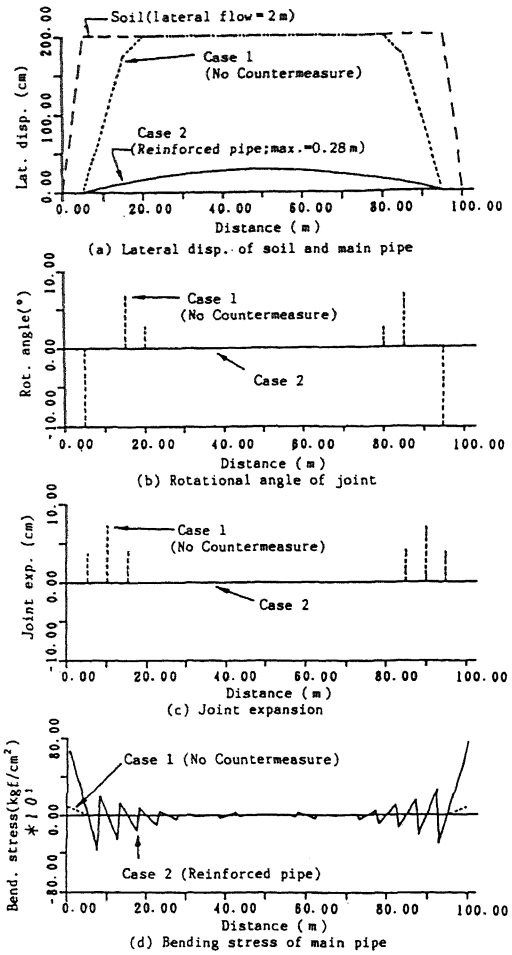

Fig.8 Response of Pipes for Lateral Displacement of Soil [Cases 1 and 2 ; Soil disp.=2.0m, GM-type joint]

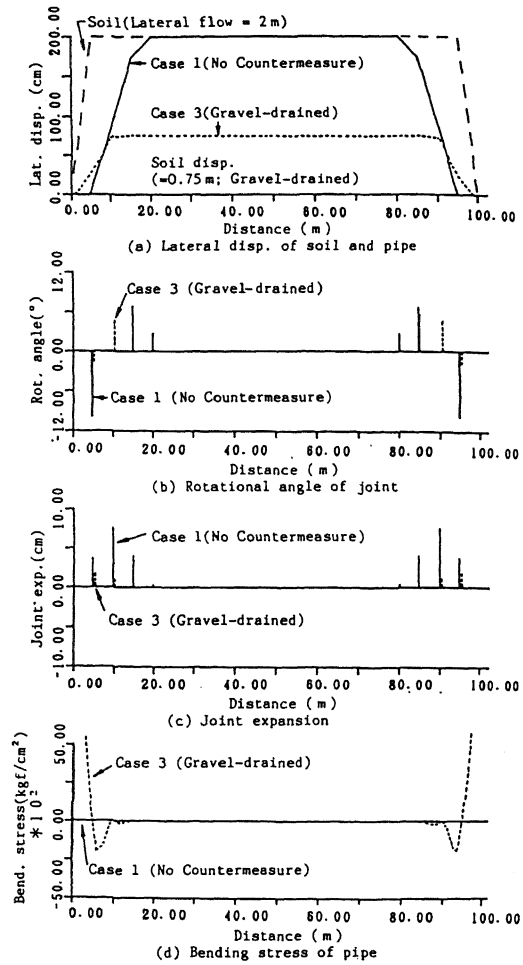

Fig.9 Response of Pipes for Lateral Displacement of Soil [Cases 1 and 3 ; Soil disp.=0.75m, GM-type joint]

termeasure pipe cannot resist the deformation of the gravel-improved soil and finally causes perfect failure by bending enforcement at L-NL boundary (:lowest diagram(d)).

5.3 Sand compaction pile vs. no countermeasure

The sand-compaction pile (SCP) method is one of most popular works for preventing the soil liquefaction in Japan. From experimental results of SCP method (Tanaka, 1991), it is noticed that stiffness of soil improved by SCP increases over ten times as large as that of no-countermeasured soils. Further, referring to analytical results for soil flow (Shirinashihama 1991), displacements of soils improved by SCP decrease about 25% as large as that of no-countermeasured soils. In Fig.10 (a), displacements of pipes for Case 4 (improved by SCP) are reduced to 0.50 m against the displacement of 2.0 m of no-countermeasured soil. However it is also shown in Fig.10 (b) and (c) that rotational angle and expansion of a joint are not so small compared with the displacement and still keep dangerous level at L-NL boundary.

5.4 Sheet pile vs. no countermeasure

In Fig.11 the effectiveness of soil for Case 5 (:by sheet pile) is represented and compared with Case 1 (:no countermeasure). The soil parameters in Case 5 are determined from the results studied by Akiyoshi (1991). According to the analysis using subgrade reaction of soil in the references, the soil displacement for Case 5 becomes 0.5 m.

In Fig.11(a) the displacements of pipes buried in

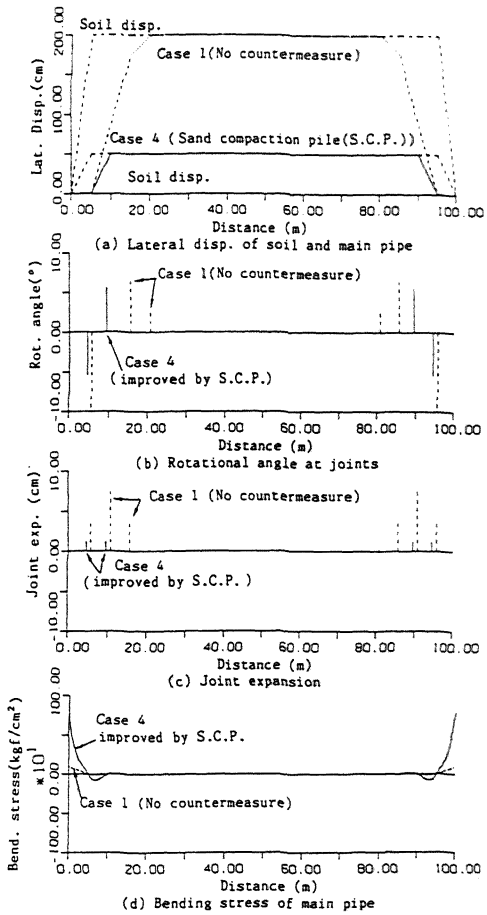

Fig.10 Response of Pipes for Lateral Displacement of Soil [Cases 1 and 4 ; Soil disp.=0.5m, GM-type joint]

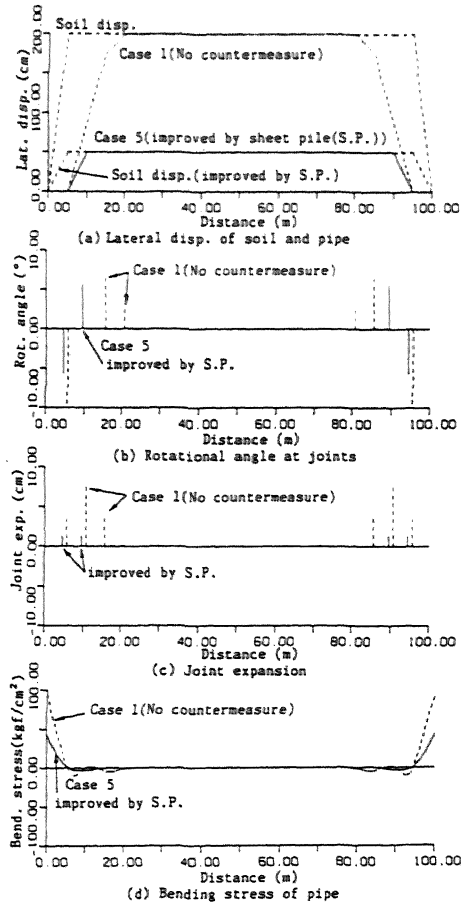

Fig.11 Response of Pipes for Lateral Displacement of Soil [Cases 1 and 5 ; Soil disp.=0.5m, GM-type joint]

the soil reinforced by sheet piles (:Case 5) decrease 25% as large as one of no-countermeasured soil (:Case 1), but the displacements of joints in the diagrams (b) and (c) are not allowable yet. These results are almost same as the results of SCP method in Fig.10 (:Case 4), but for bending stress in Fig.10 (d) and Fig.11 (d) it may be said that the sheet pile method is more effective at L-NL boundary than SCP method.

5.5 Pile-supporting vs. no countermeasure and reinforced pipes

Effectiveness of another anti-liquefaction method which supports a new pipeline by vertical steel piles (the diameter=319 mm, thickness=7 mm) as shown in Fig.3 [f](:Case 6) is compared both with the reinforced pipe method(:Case 2) and no countermeasured case (:Case 1) in Fig.12. In this case a vertical profile of the ground at Kawagishi-cho, Niigata city, Japan (Daibuzono, 1988) is used and the vertical variation of stiffness of liquefied soils around the pipes represented as a coefficient k of subgrade reaction is approximately formulated by the indoor experiment for piles (Matsumoto, 1987):

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

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.12(a) shows that the effectiveness of end-bearing piles (:d=24m) are comparable with the proposed method. Therefore deep embedment of piles becomes similarly high-effective anti-liquefaction method as well as the reinforced one.

6 CONCLUSIONS.

In this paper a simple and auxiliary structural-rein-

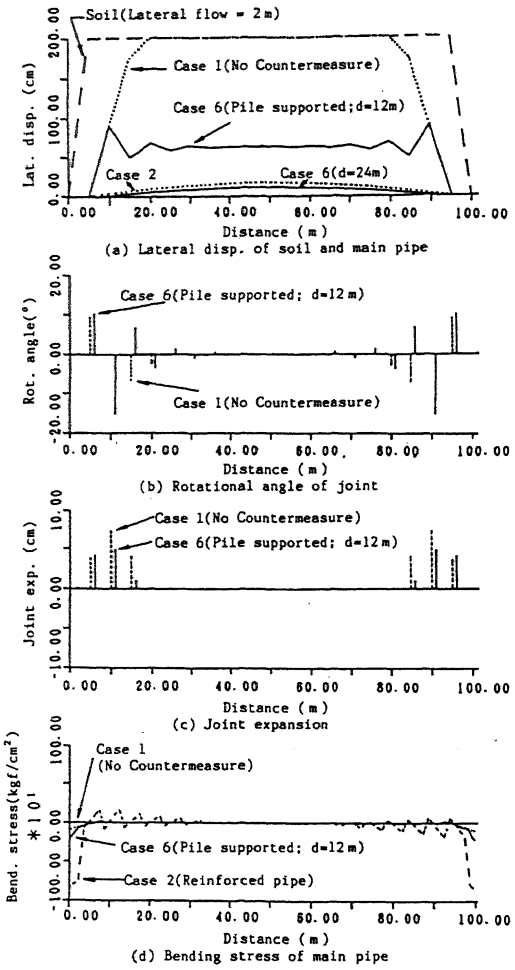

Fig.12 Response of Pipes for Lateral Displacement of Soil [Cases 1, 2 and 6 ; Soil disp.=2.0m, GM-type joint]

forcing method is presented and studied together with the existing several anti-liquefaction methods, comparing with their effectiveness for the prevention of liquefaction-induced huge deformations of pipelines as well as liquefied soils.

It is shown that popular pipelines with flexible joints do not work so effective to resist and prevent such large displacements for lateral flow of liquefied ground that the stresses of pipes and strains of joints concentrate closely at the liquefied-nonliquefied boundaries and exceed the allowable capacities of stress and deformation.

Other anti-liquefaction procedures of the pile supporting, the sand-compacted piles and the sheet piles methods are effective for preventing large displacements of pipelines except for rotational angles.

The proposed method succeeds to prevent the stress and strain concentrations at joints by reinforcing the bending resistant of buried pipelines for large enforced displacement. From economical view point the proposed method may be advantageous because used iron pipes are available as stiffening pipes in proposed reinforced system.

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