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SEISMIC BEHAVIOR OF PIPELINES DURING TRANSVERSE LIQUEFACTION CONSIDERING EFFECTS OF GROUND DEFORMATION

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SUMMARY

Permanent ground deformation (PGD) induced by soil liquefaction is classified as a main cause of damage of pipeline structures. In this study, for dynamic analysis of continuous pipeline structures against transverse permanent ground deformation, the decrease of soil stiffness caused by excess pore water pressure is represented to the value of soil spring constant depending on time and location. Energy dissipation effect is considered through geometrical and material properties. Numerical algorithm is developed based upon finite element method and Newmark explicit-implicit scheme. Various analyses are performed using different parameters such as earthquake intensity, width of PGD and effective soil mass coefficient. Through these procedures, influential factors on dynamic behavior of pipeline structures are examined.

DEFINITION AND CHARACTERISTICS OF PERMANENT GROUND DEFORMATION

Permanent Ground Deformation

Permanent ground deformation (PGD) is defined as large scale ground displacement. Its causes are classified as follows: soil liquefaction, sliding and fault movements. Among these three causes, sliding and fault movements have shown a low occurrence frequency. On the contrary, several cases in history have shown that soil liquefaction happen even more frequently and induce large PGD, which generates severe damage to pipeline structures [M.Hamada, T.D. O`Rourke, 1992]. The occurrence of liquefaction causes increase in excess pore water pressure and decrease in effective stress. Especially this decrease of effective stress produces volumetric change, attenuation of soil stiffness and PGD concurrently.

Pipeline Behavior against Permanent Ground Deformation

Pipeline structures which are usually buried at shallow depth have possibilities of local or whole failure caused by PGD. Thus the behavior of pipeline structures depends on the orientation of buried pipeline against the direction of PGD. Fig. 1 shows schematic failure modes of pipeline structures. Most frequent failure cases in history have shown following characteristics. First, perpendicular crossing or arrangement of pipeline – transverse PGD: Fig. 1(b) – makes it more possible for pipeline to break or fail. Second, developed shape of PGD is in the symmetric pattern, which is influenced by geographical or topological conditions. Thus, this study is focusing on the perpendicular crossing case.

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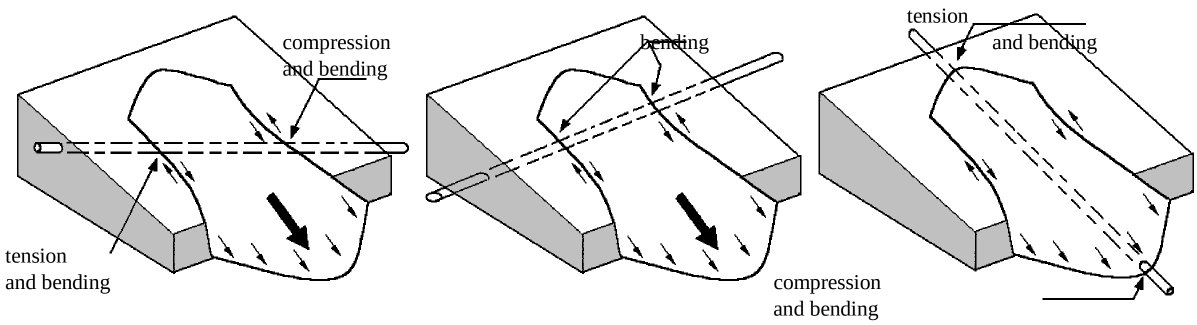


(a) Random crossing **(b) Perpendicular crossing** **(c) Parallel crossing**

Fig. 1: Typical pipeline behavior against PGD

MODELING AND CONSTRUCTION OF SYSTEM EQUATION OF MOTION

Modeling of Whole System

In order to perform dynamic analysis of continuously buried pipeline against transverse PGD, the stiffness, mass, damping of pipeline and surrounding soil should be considered. Whole system which has a schematic diagram as shown in Fig. 2 is regarded as a finite element beam model presented in Fig. 3.

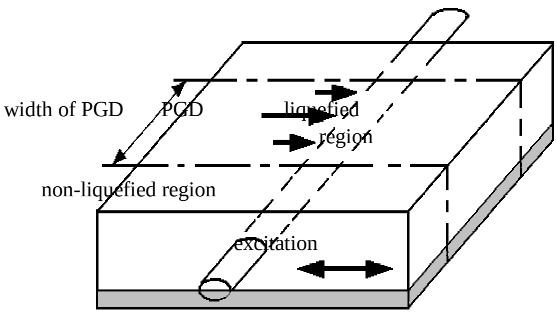


Fig. 2: Schematic diagram of whole system

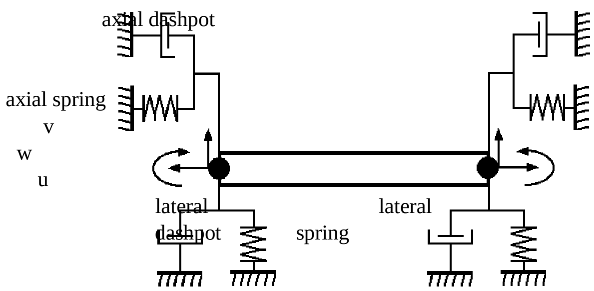


Fig. 3: Finite element model of pipeline

A beam model based on the theory of beam on elastic foundation is used for the pipeline buried between non-liquefied and liquefied region. Three degrees of freedom in axial, lateral and rotational direction are considered at each node. Also spring and dashpot elements are modeled in axial and lateral direction.

Modeling of Decrease of Soil Stiffness

When PGD occurs under soil liquefaction environment during an earthquake, the increase of excess pore water pressure accompanies the decrease of soil stiffness. Therefore it is necessary to quantify the change of soil stiffness to model PGD. It is well known that there are several types of pore water generation curves according to specific soil conditions such as relative density, initial stress, grain size and drainage condition. Fig.4 shows representative functions obtained by experiments [H.B.Seed etc, 1976]. Soil stiffness decrease function shown in Fig. 5 can be obtained by relating excess pore water pressure with cyclic ratio –type C– in Fig. 4 into change of soil stiffness with time ratio. In this study average function like Eq.1, Eq. 2 is used to simulate decrease of soil stiffness which stand for PGD effects.

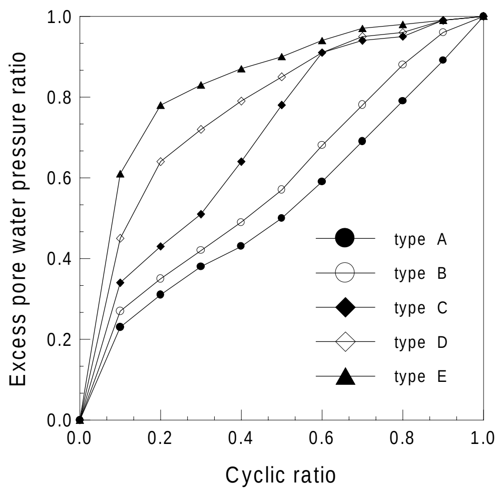


Fig. 4: Pore water pressure generation curve

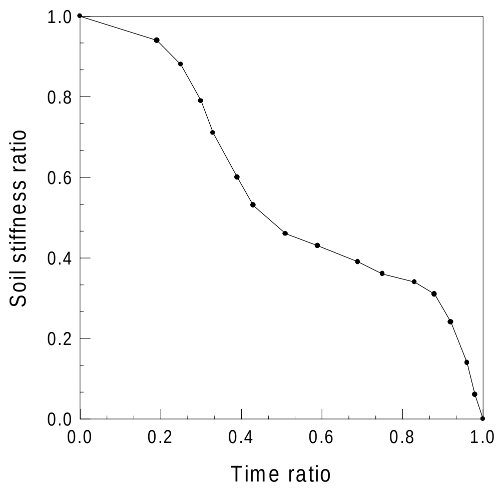


Fig. 5: Soil stiffness decrease function

$$k_l(t) = 9.0 \cdot \gamma(\alpha) \cdot \left[\sigma'(t) \cdot \left\{0.5 - \sin^{-1} \cdot \left(2.0 \cdot (t/t_L)^{-\beta} - 1.0\right)/\pi\right\}\right]^{0.54} \tag{1}$$

$$k_a(t) = 1.838 \cdot k_l(t) \tag{2}$$

Here $k_l(t)$, $k_a(t)$ is the lateral, axial stiffness coefficient of soil. $\gamma(\alpha)$, β is constant decided by experiments. Also, t is a duration time of ground excitation and t_L is a specific beginning time of generation of PGD influenced by numerous factors.

Modeling of Surrounding Soil and Energy Dissipation Effects

During an earthquake or a ground excitation, certain amount of surrounding soil moves with the pipeline. This amount of soil is called added or effective soil mass. The effective soil mass increases rapidly from low burial depth to radius ratio, but approaches a constant value when the ratio is greater than 18 [R.A.Parmelee etc, 1975]. During the liquefaction process, the effective soil mass decreases with time. In this study, it is assumed that the effective soil mass decreases proportionally to the value of soil spring constant in the liquefaction zone. On the while the energy dissipation effects are considered into geometrical and material damping term. The results of previous studies are referenced for each case [G.Gazetas, 1983 and I.Ishibashi, 1981].

Construction of System Equation of Motion

The system equation of the motion of pipeline structures against transverse PGD considering the effects of liquefaction can be represented as follows.

$$[M_t]_{n\times n}\{\ddot{u}\}_{n\times 1} + [C_t]\{\dot{u}\}_{n\times 1} + [K_t]_{n\times n}\{u\}_{n\times 1} = -[M_t]_{n\times n}\{\ddot{u}_g\}_{n\times 1} - [K_p]_{n\times n}\{u_g\}_{n\times 1} \tag{3}$$

Here, subscript "*n*" stands for total degrees of freedom of system. $[M_t]$ is the sum of the mass matrix of structure $[M_p]$ and soil $[M_a]$. $[C_t]$ is the sum of the geometrical $[C_g]$ and material damping matrix $[C_m]$. $[K_t]$ is the sum of the stiffness matrix of structure $[K_p]$ and soil $[K_s]$. On the other hand, u, $\dot{u}$ and $\ddot{u}$ indicates relative displacement, velocity and acceleration of pipeline, while u_g, $\ddot{u}_g$ displacement and accelearation of ground. Notice that mass, damping and stiffness matrix of entire system all changes with time.

NUMERICAL ANALYSIS

Material Property and Input Earthquake

In this study, material properties of 100A type steel pipe are used and its geometrical dimensions are tabulated in Table 1 with general properties of surrounding soil. The value of lateral soil stiffness constant is estimated by standard of unit width and effective soil mass coefficient 1.1. Tokachi earthquake and Eastchiba earthquake are selected as the seismic input data. The value of maximum acceleration of two earthquake data is similar. But the value of ground displacement in Tokachi earthquake is much larger. Changes in ground displacement and excess pore water pressure ratio resulting from the input of seismic forces of Tokachi earthquake are shown in Fig. 6. As shown in Fig. 7, bending stress suddenly jumps about 10 sec – pore water pressure ratio is over 0.5 – i.e PGD begins to happen. It reflects dominant influence of generation time of PGD, t_L. Comparing with Yasuda`s research [S.Yasuda, 1992] and pseudo static analysis result in which only the effect of ground displacement is considered, two distinctive characteristics are observed. One is fluctuation of bending stress and the other is that bending stress in dynamic analysis is much greater than other research. These things can be only seen in dynamic analysis. The fluctuation of bending stress reflects effects of acceleration and inertia force. Moreover the value of bending stress which is larger than the other results at final time step signifies the importance and need of dynamic analysis.

As seen from Fig. 8, in case of Eastchiba earthquake that has smaller ground displacement under similar acceleration condition, fluctuation phenomena declines and the value of bending stress becomes much smaller. These phenomena suggest that dynamic behavior of pipeline against PGD is more affected by ground displacement. To visualize the effect of ground displacement, analysis is executed using artificial earthquake that has ground displacement multiplied by Tokachi case. As seen in Fig. 9, under same acceleration condition the greater ground displacement the larger bending stress and the smaller extent of fluctuation. All these things imply that consideration of dynamic effect is indispensable for more enhanced analysis especially when ground displacement is somewhat large.

Table 1: Dimension and property

Steel Pipe	Outer Diameter	**cm**	11.43
	Thickness	*cm*	0.60
	Young`s Modulus	*Mpa*	2.04 x 10^5
	Moment of Inertia	*cm^4*	300.21
	Allowable Stress	*Mpa*	2.50 x 10^2
Soil	Burial Depth	*cm*	3.00 x 10^2
	Lateral Soil Stiffness	*Mpa*	0.60
	Effective Stress	*Mpa*	0.025

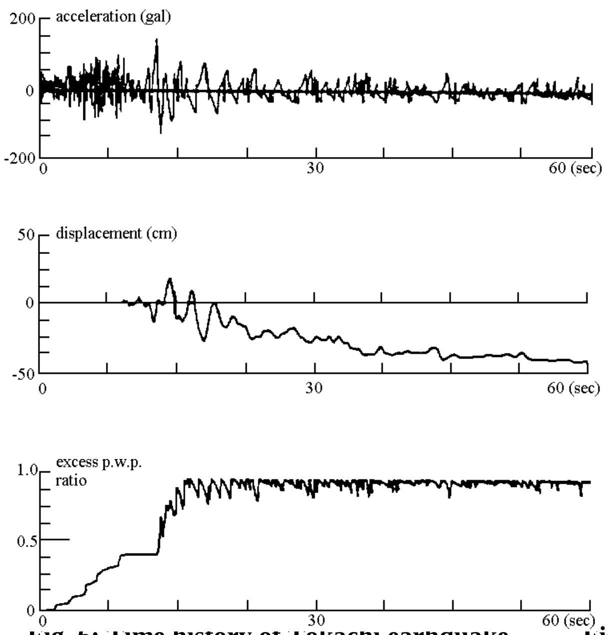


Fig. 6: Time history of Tokachi earthquake

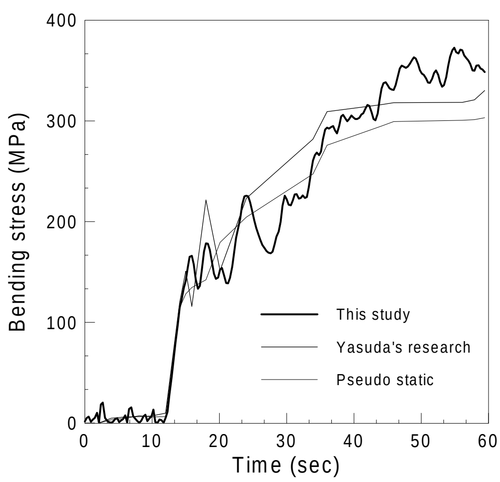
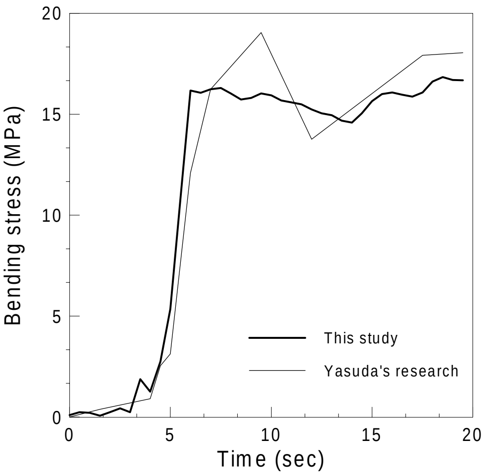


Fig. 7: Bending stress under Tokachi earthquake



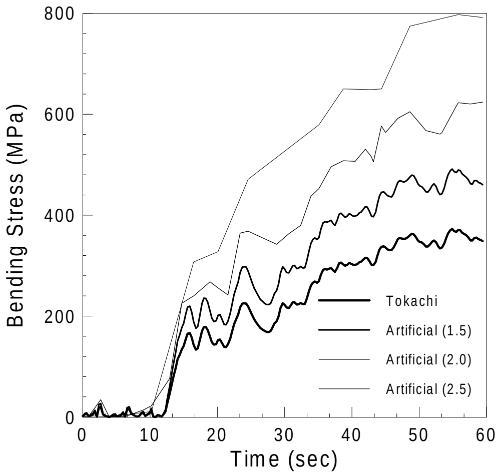
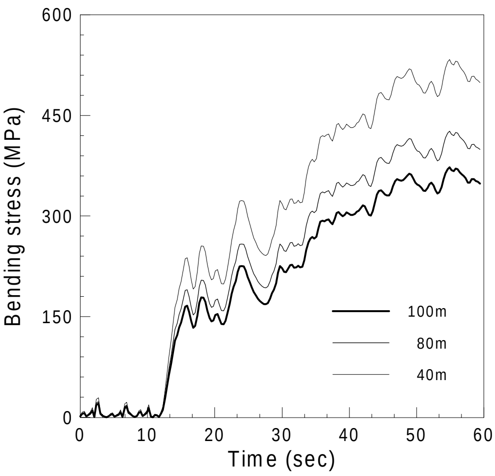


Fig. 8: Bending stress under Eastchiba earthquake **Fig. 9: Bending stress under artificial earthquake**

The Effects of Width of Permanent Ground Deformation

Analyses are performed changing the width of PGD as a parameter. For the width of PGD as 40m, 80m, 100m, Fig. 10 and Fig. 11 show that the narrower the width of PGD the larger bending stress. This tendency has been well known in previous studies whether the magnitude of ground displacement is large or not. From these facts it can be concluded that pipelines have high chance to fail in case of PGD with narrow width.



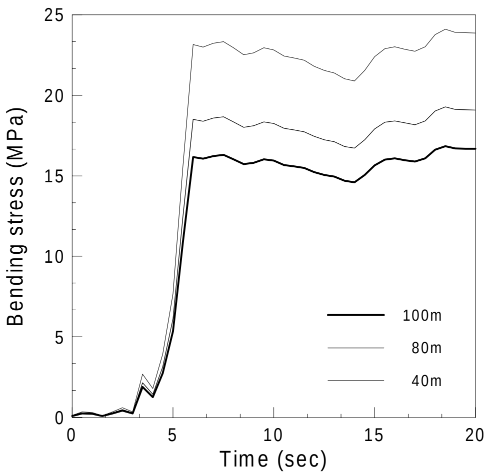


Fig. 10: Effects of width of PGD(Tokachi) **Fig.11: Effects of width of PGD(Eastchiba)**

The Effects of Effective Soil Mass

Taking effective soil mass coefficient as a parameter which is changed from 0.7 to 1.5, pattern of bending stress change according to that is shown in Fig. 12 and Fig. 13. Increase of effective soil mass coefficient means increase of burial depth of pipeline in same diameter. With same burial depth increase of coefficient indicates decrease of diameter. As seen from Figs., the larger effective soil mass coefficient the larger bending stress. Increase of bending stress might be caused not only by increase of soil mass but also by decrease of pipeline stiffness. It can not be said that the influence of pipeline stiffness is more dominant than mass in dynamic behavior of pipeline structures against transverse PGD. However, general fact that pipeline with relatively small diameter is liable to fail more easily can be reconfirmed from Fig. 12,13.

The Effects of Soil Stiffness Function

Analyses are performed to verify the influence of soil stiffness decrease function. Of five pore water generation curves (Fig. 4), two extreme type A and E were chosen and transformed into soil stiffness decrease function. As seen in Fig. 14 and Fig. 15, types of soil stiffness function do not have much effect on the behavior of pipeline against transverse PGD. Under the soil liquefaction induced PGD environment, soil stiffness function is affected by many factors. So, quantifying soil stiffness function is a complex problem and at the same time an important issue in civil engineering. Nevertheless, the results show that types of soil stiffness function do not have much effect on behavior of pipeline. This tendency clarifies that in dynamic analysis of pipeline considering effects of PGD decrease of soil stiffness in itself is more important than the type of soil stiffness function.

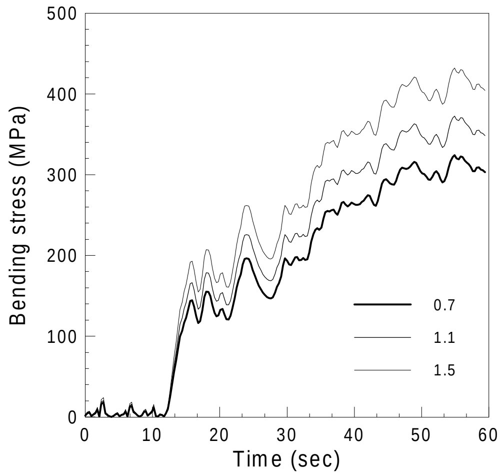


Fig. 12: Effects of effective soil mass(Tokachi)

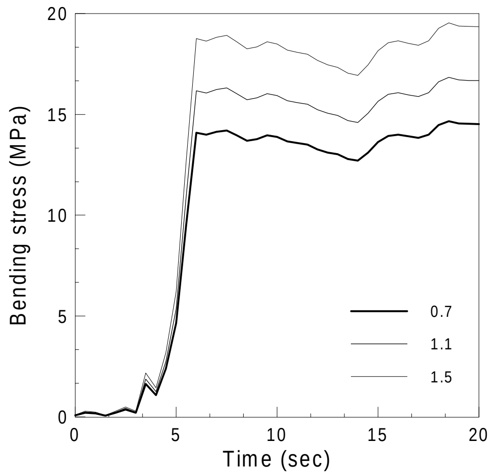


Fig. 13: Effects of effective soil mass(Eastchiba)

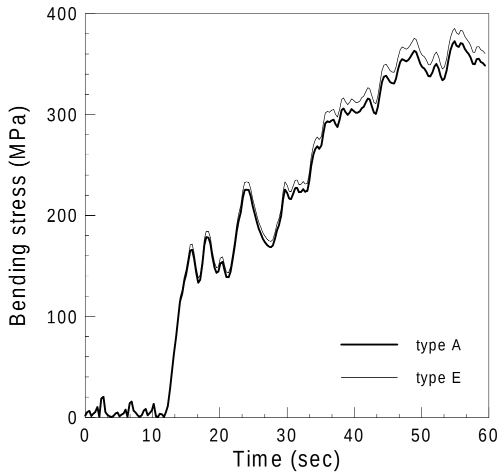


Fig. 14: Effects of soil stiffness function(Tokachi)

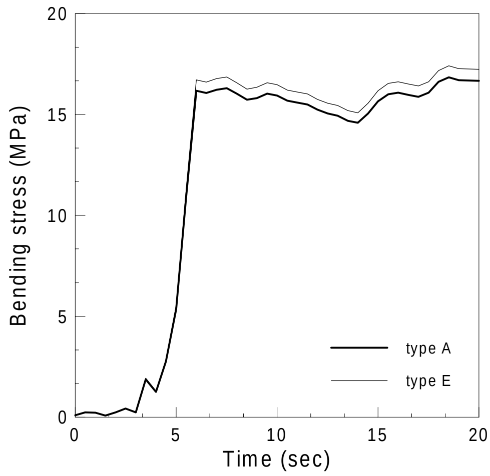


Fig. 15: Effects of soil stiffness function(Eastchiba)

CONCLUSIONS

In this study, seismic analyses are executed for the behavior of buried pipeline structures against transverse permanent ground displacement and obtained following conclusions.

1. When permanent ground displacement occurs, dynamic analysis is needed to expect behavior characteristics of pipeline more precisely.

2. The narrower the width of PGD, the larger bending stress is. For relatively narrow width of PGD, the possibility of damaging the pipeline tends to increase without consideration of the magnitude of earthquake

3. Types of soil stiffness decrease function do not have much effect

4. When PGD begins to happen, the specific time of soil stiffness loss has a great influence on the behavior of pipeline.

ACKNOWLEGMENTS

This research has been funded by a grant from the Korea Gas Co. R&D Center and KISTEP to Yonsei University.

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