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SEISMIC RESPONSE OF PIPELINE SYSTEMS BURIED IN DIPPING SOIL LAYERS

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SUMMARY

Analysis of seismic response of pipeline systems buried in surface layer with irregular boundaries is presented here. A soil model which consists of two-dimensional upper and lower layers is solved by the boundary element method for SH-type earthquakes. For the excitation of surrounding soil, strain and joint expansion of pipes under imperfect bonding at the soil-pipe interface are analyzed. Results show that proposed method is fairly proper to express the phenomenon of strain concentration at the joints of pipes and a conventional aseismic design guideline overestimates the effect of slippage at the soil-pipe interface.

INTRODUCTION

It may be noted from the observations of seismic damages that most of pipelilne failures in Japan have occurred at the joints in poor soils or near dipping boundaries of soil layers. So much effort has been devoted to the investigations of buried pipeline response to earthquakes and establishment of effective aseismic design procedures. However seismic damages of pipelines do not seem to decrease yet, as has been seen in recent earthquakes, Off Miyagi Pref. earthquake (1978) and Middle Japan Sea earthquake (1983). Hence to stimulate understanding on the mechanism of pipeline damages, presentation of a reasonable soil-pipe model to express the strain concentration at the joint is required. With respect to the effect of irregularity of soil boundary on the seismic response, most of works have been achieved by using the conventional numerical procedures, finite element method (FEM) and boundary element method (BEM), and it has been noticed that displacement or strain response of ground surface are increases near or on dipping soil layers(Refs. 1,2). Regarding pipe response embedded in a soil layer, two different approaches have been taken according to the definition of surrouding soil. One is based on the use of spring constant of soil which is usually decided empirically and therefore cannot describe the dynamic characteristics of soil deposite(Ref. 3). Another is based on coupling between pipe and spatial soil which is mostly processed by FEM or BEM for sinusoidal excitation(Refs.4,5). However so far adjustment of the results by both approaches does not seem to be successful.

This paper which is basically on the latter approach and the extension of our previous works(Refs. 6,7) aimes to investigate the effect of irregularity of soil boundaries on the seismic response of pipelines and present a rough estimation of the strain and joint expansion. Results obtained are compared with the guideline for an aseismic design of gas pipeline(Refs. 8,9) in Japan for normalized El Centro earthquake (1940). Analysis is performed based on the dynamic coupling of an infinite soil layer and pipelines through the frictional interface.

METHOD OF ANALYSIS

In this study two-dimensional elastic soil layer model which is subjected to SH-type earthquakes is used as shown in Fig.1 in which V_1, V_2 are shear wave velocities of surface and base layer, respectively, and H_1, H_2 are thickness of side (thin) and central (thick) areas, respectively. Further the surface layer is assumed to have hysteretic damping and irregular boundary areas in which "irregularity" is defined as dipping of boundary planes. Using BEM, equations of motion of the surface layer under steady harmonic vibration are formulated in the matrix form (Ref. 1), and solved by considering the boundary conditions of displacement and traction of input and scattered waves at the surface-base layer interface. Thus displacements at the ground surface derived are used for the frequency response functions (FRF) of displacement to displacement conversion type.

Next the concept of seismic response analysis of a buried pipeline may be stated below, in which the main pipeline consists of periodical connections of pipes and joints as shown in Fig.1 and treated as a statically equivalent uniform one, and branch pipes are assumed to be elastically connected both to the main pipes and structures(Refs.6,7). First step begins with the decision of slip displacement U(f) in accordance with the displacement $U_s(f)$ of surrounding soil because FRF of buried pipeline depends on U(f). Here is an example of spectral displacement amplitude $U_s(f)$ of the soil and U(f) of the slip for El centro earthquake (1940) (Fig.2), in which U(f) is shown by asterisks along with the critical slip amplitude U_{cr}(solid line) and $U_s(f)$ by white circles. If $|U_s| < U_{cr}$, slip does not occur and therefore U=0 which is shown approximately on the frequency axis. However, if $|U_s| > U_{cr}$, slip takes place and U is computed in accordance with the closed form solution of soil-pipe interaction as the asterisks over U_{cr} in Fig.2. The diagram denotes that slip becomes perfect when $|U_s| \gg U_{cr}$, and imperfect when U_s is close to U_{cr}. Thus employing FRF $H_p(f)$ of a pipeline which can be determined based on coupling with surrounding soil, spectral displacement amplitude $U_p(f)$ of the pipeline may be given as the product of FRF of the ground surface and Fourier transform of the input displacement at the base layer. Strain of the pipeline is also obtained by taking similar process. Thus finally root mean square(rms) strain and joint expansion of the pipeline are evaluated directly from the spectral strain amplitudes, and then the time-histories of the response are obtained from the inverse Fourier transform.

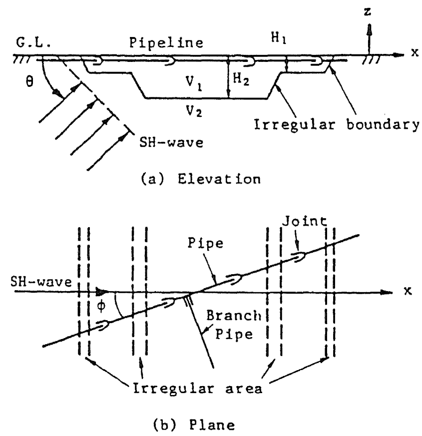


Fig.1 Configulation of Soil Layer and Pipeline

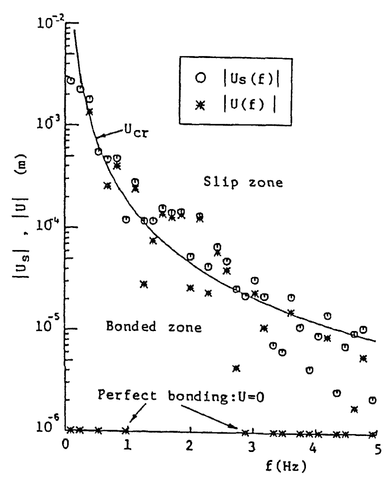


Fig.2 Spectral Displacement and Critical Slip Amplitude

NUMERICAL RESULTS

Standard values of the parameters of earthquakes, soils and pipes used for numerical computations are as follows; shear wave velocities of surface and base layer are, respectively V_1=100m/s and V_2=400m/s, thickness of thin(both-sided) and thick area of surface layer, respectively, H_1=20m and H_2=70m, bottom length of thin and thick area, respectively, 0.5 km and 1.0 km, horizontal incident angle to pipe $\phi=45°$, hysteretic damping constant=20%, ratio of frictional slip stress to shear modulus of soil $\overline{\tau}_s=\tau_s/G=10^{-3}$, radius of main and branch pipe=0.3m and 0.1m respectively, wave velocity of pipe V_p=4 km/s, and maximum acceleration of reference earthquake [=El Centro earthquake (1940)], A_{max}=100gal, in the base layer.

First as the input to the pipe, soil strain at the ground surface is investigated which will be plotted in Figs.3 and 4 for the incident angle θ , layer thickness H_2 . Fig.3(a) is the diagram of the distribution of root mean square (RMS) strain of soil at the ground surface for three incident angles. A horizontally propagating earthquake (:El Centro earthquake(1940)) not only gives sharp strain concentration on irregular areas, especially at the transition area of thin to thick layer, but also raises the strain of the central area of the surface layer. Soil strain distributions are also plotted in Fig.4(a) for three thicknesses of the bottom area of the surface layer. Soil strain increases and concentrates highly at the irregular area with increasing layer thickness.

For the excitation of surrounding soil, RMS distributions of strain and joint expansion of the pipe are plotted in Figs.3(b),(c) and 4(b),(c) for various slip stresses $\overline{\tau}_s$ in the case of $\theta=0°$. As shown in Figs.3(b),4(b), not only a local concentration of pipe strain at the irregular area but also high-level strain distribution even on the central area of the surface layer generates, but small slip stress releases it because of slippage. Figs.3(c),4(c), however, describe increase of joint expansion of pipe with decreasing slip stress. Thus the relation between pipe strain and joint expansion is complementary.

From practical view point, it may be important to present the seismic response curve of pipe strain and joint expansion in terms of slip stress and pipe length l as shown in Figs.5 and 6 in which solid and broken lines show, respectively, the cases for No.1 point (irregular area :see Fig.5) and No.2 point (center of parallel boundary area). Fig.5 denotes that there exists a critical slip stress $\overline{\tau}_{cr}=\tau_{cr}/G$ as the break-loose point of soil-pipe interface which increases with decreasing shear wave velocity V_1 of surface layer, and soft soil(small V_1) is easy to enter the imperfect bonding which releases pipe strain. Also the diagram implies that pipe strain in perfect bonding state varies approximately in inverse proportion to V_1 and is amplified at irregular boundary area.

However one of essential factors to cause seismic damages of pipelines may be excessive joint expansion which is defined as the accumulation of released pipe strain due to slippage. Amplification effect of joint expansion by irregular boundary also appears in Fig.6. Long pipe generates large joint expansion by slippage which may be fatal to many joints except for mechanical ones. However joint expansion of standard size pipe (length =5 meters) is so small (less than 0.2 cm in the diagram) that, though it may be still destructive to screw or flange-type joints, it is absorbable in usual mechanical joints. Thus the figure recommends dense attaching of joints at irregular boundary area because short length pipe is effective to prevent slippage and accumulation of strain at the joints.

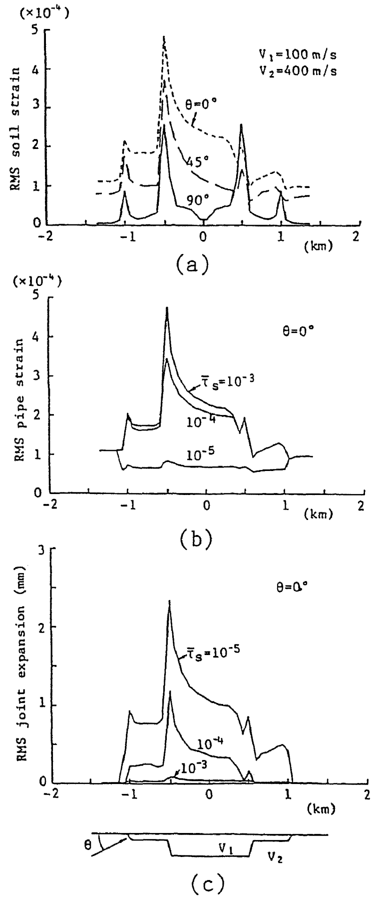


Fig.3 Distribution of RMS Soil Strain, Pipe Strain and Joint Expansion

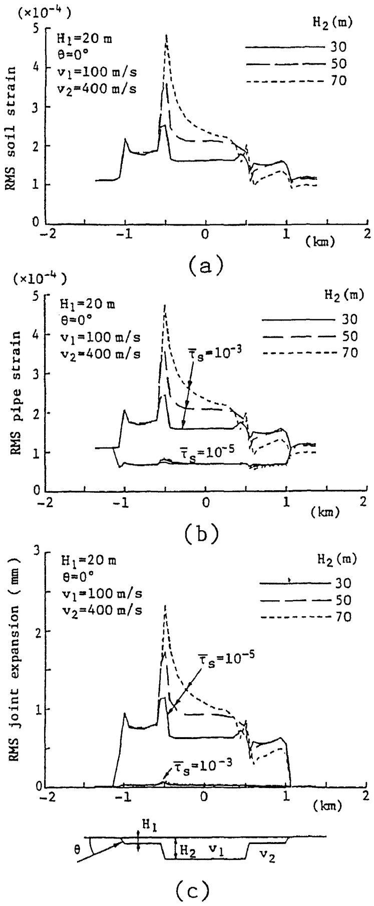


Fig.4 Distribution of RMS Soil Strain, Pipe Strain and Joint Expansion

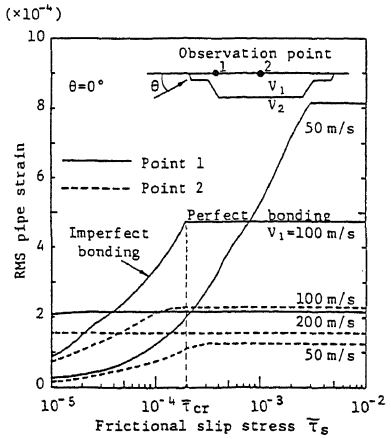


Fig.5 RMS Pipe Strain versus Frictional Slip Stress

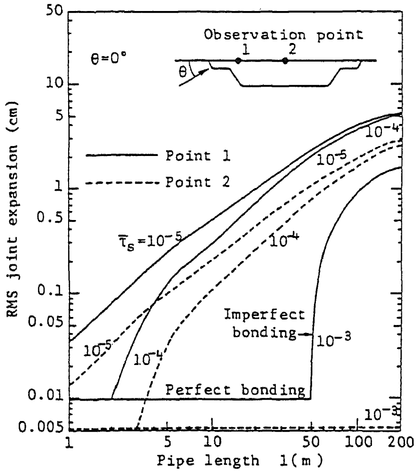
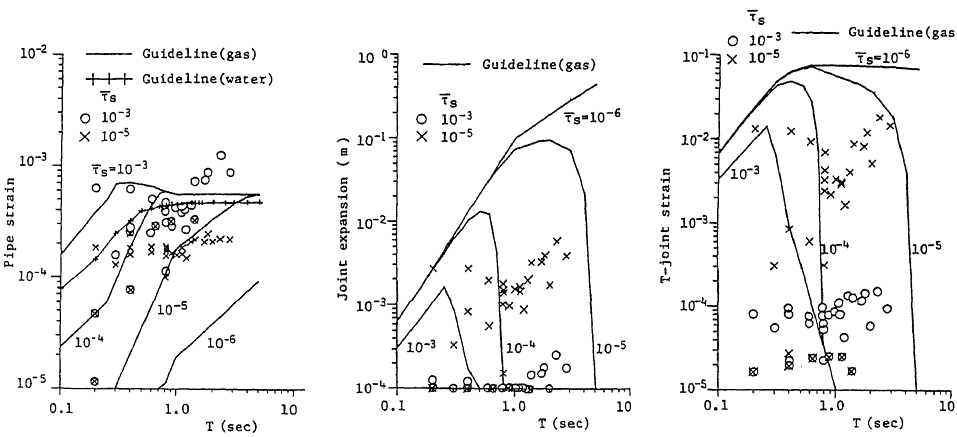


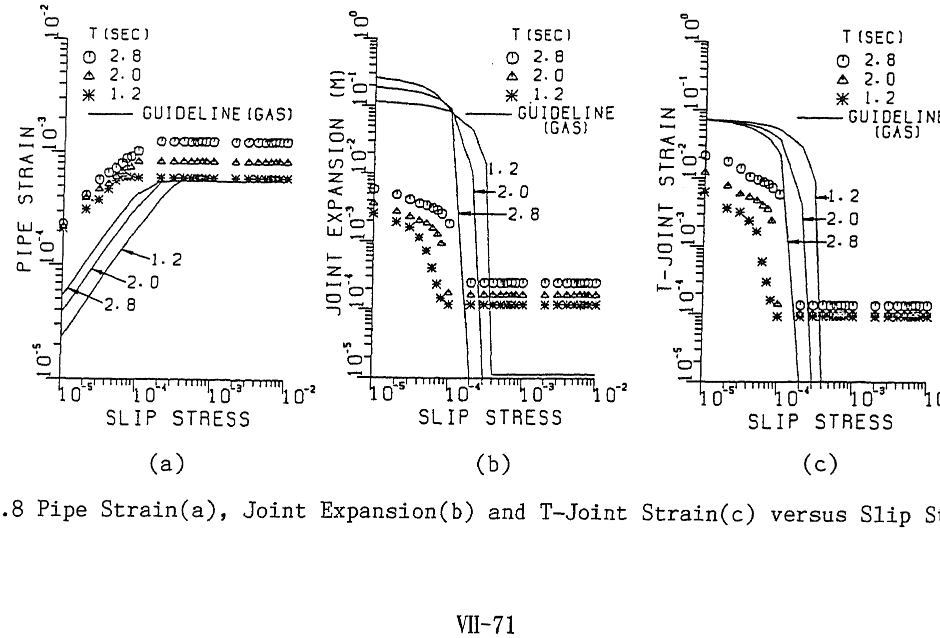
Fig.6 RMS Joint Expansion versus Pipe Length

Now compare the pipe strain and joint expansion by proposed mehtod with the guideline for aseismic design of gas pipelines, partially using the method of M. Shinozuka and T. Koike. According to the guideline, soil displacement and strain in a surface layer with parallel boundary are basically derived by horizontal seismic coefficient and natural period T=4H/V(H:thickness, V:shear wave velocity of surface layer). This procedure also applies irregular boundary area in which H is replaced with the depth to dipping plane. Fig.7(a) is the diagram of pipe strain for the case of irregular (dipping) boundary in which solid line denotes the guideline and symbolic marks maximum pipe strain by proposed method. The diagram shows that proposed pipe strains slightly exceed the guideline for $\overline{\tau}_s=10^{-3}$ and the guideline may provide a comparable estimate of pipe strain for nearly bonding case ($\overline{\tau}_s=10^{-3},10^{-4}$). Figs.7(b),(c) are the diagrams of joint expansion and strain of branch pipe connected to the main pipe by T-joint respectively, in which solid lines and symbolic mark denote same descriptions as Fig.7(a). If slippage occurs, joint expansion or T-joint strain increases, but the guideline may overestimate the effects of slippage.



(a) (b) (c)

Fig.7 Comparison of Proposed Pipe Strain(a), Joint Expansion(b) and T-Joint Strain(c) with a Guideline(gas)



(a) (b) (c)

Fig.8 Pipe Strain(a), Joint Expansion(b) and T-Joint Strain(c) versus Slip Stress

Figs.8(a),(b),(c) are the diagrams which show the seismic response of pipe strain, joint expansion and T-joint strain respectively in terms of slip stress. In Fig.8 solid lines and symbolic marks show, respectively, the guideline and the proposed method for irregular boundary area. Figs.8(a),(b),(c) denote that both seismic responses by the proposed method and the guideline similarly change with slip stress, and the guideline may estimate pipe strain smaller, joint expansion and T-joint strain larger than the proposed method. For small slip stress (soft soil) the guideline recommends too excessive design values of joint expansion and T-joint strain which is surely in safe side but will be over the absorbing capacity of even in recently developed aseismic joints.

CONCLUSION

In this paper, response of strain and joint expansion of pipes buried in irregularly bounded soil layers during earthquakes have been investigated, coupling the boundary element method with our previously presented procedures. Results obtained are summarized as follows:

(1) Proposed method is effective to express strain concentration at the pipe joints by slippage during earthquakes.

(2) Surface layer induces high strain concentration due to the irregularly bounded area and horizontally propagating earthquakes.

(3) Small slip stress releases pipe strain by slippage.

(4) For uniform layers proposed pipe strain is comparable with a conventional guideline for aseismic design of gas pipelines. However, for irregularly bounded layers, the guideline overestimates effects of slippage, compared with proposed method.

(5) At irregular boundary area, dense attaching of joints is recommended to prevent strain accumulation by slippage.

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