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IMPROVEMENT AND SUGGESTION ON SEISMIC DESIGN METHOD OF BURIED PIPELINE WITH FLEXIBLE JOINTS

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In this paper the authors proposed new design formulae for estimating stresses in buried pipeline with flexible joints by means of the seismic deformation method. The formulae are simpler than that applied in seismic design guidelines for buried pipeline in Japan. Empirical formulae in Guideline of Common Utility Ducts of Japan for estimating pipeline's stress during earthquake agree well with the proposed complete formulae in limited parameter region, but may give quite different results beyond the parameter region. The authors also suggested a calculation procedure to estimate the stress and deformation in buried pipeline caused by settlement due to an earthquake.

Key Words: *flexible joint, buried pipeline, seismic deformation method, settlement due to earthquake*

1. INTRODUCTION

The seismic design of buried pipeline with flexible joints includes two parts: check account the pipeline's strength and the joint's deformation. Some seismic design guidelines for buried pipelines with flexible joints in Japan[1),2),3)] defined design formulae to estimate the pipeline's stress and joint's deformation during an earthquake based on the seismic deformation method (SDM). According to the fact that the rigidity of the flexible joint is rather smaller than that of the pipeline's segment, the formulae can be obtained by a beam theory on an elastic foundation satisfying the boundary conditions of free stress in two segment ends. But the formulae for estimating the pipeline's stress are quite complicated, therefore, empirical formulae are applied in The Guideline of Common Utility Ducts (CUD) to simplify the calculation[4)]. The applicable region of the proposed empirical formulae is limited in a few parameters. In order to improve the above-mentioned questions, the authors derived formulae to estimate the pipeline's stress and joint's deformation based on the same boundary conditions. The new results showed that:
(a) the formulae defined in seismic design guidelines can be expressed in more simplified formulation.
(b) the empirical formulae applied in The Guideline of CUD of Japan may make significant errors when the parameters exceeded the suitable region.

Except the seismic ground displacement, on the other hand, the action of an earthquake should include settlements due to the earthquake (caused by liquefaction or subsidence). The authors also suggested a calculation procedure to estimate the pipeline's stress and joint's deformation under the action of the settlement due to an earthquake based on the same above-mentioned boundary conditions.

2. FORMULAE OF STRESS MODIFICATION FACTOR BY SDM

(1) Analysis in the axial direction

According to the seismic deformation method, the displacement $u(x)$ of a buried pipeline in the axial direction must satisfy the equilibrium equation

$$\frac{d^2u(x)}{dx^2} - \lambda'^2\, u(x) = -\lambda'^2\, u_G(x) \qquad (1)$$

where: $\lambda' = \sqrt{k_a / EA}$; and $k_a, EA, u_G(x)$ are the longitudinal spring constant of ground, the axial rigidity of the pipeline and the seismic ground displacement in the axial direction, respectively.

The sinusoidal ground displacement (with incident angle $\theta = 45°$), which will cause maximum axial force at the middle of the segment ($x = l/2$, l is the segment length), can be expressed

$$u_G(x) = U_G' \sin\{\frac{2\pi(x - l/2)}{L'}\} \qquad (2)$$

where: $L' = \sqrt{2}L$; $U_G' = U_G / \sqrt{2}$; and L is the wave length, U_G is the axial displacement amplitude of ground motion at the level of the pipeline.

Based on the assumption of free stress end boundary condition, under the action of the seismic ground displacement expressed in Eq.(2), the axial force developed in the pipeline segment can be obtained as (solving procedure has been omitted)

$$N(x) = \xi_1(x) N_0 \qquad (3\text{-}1)$$

where: $N_0 = EA \frac{2\pi}{L'} \alpha_1 U_G'$

$\xi_1(x)$ is the axial force modification factor

$$\xi_1(\bar{x}) = \cos\{\gamma_1(\bar{x} - \frac{1}{2})\} - \frac{\cos(\frac{\gamma_1}{2}) ch\{\beta_1(\bar{x} - \frac{1}{2})\}}{ch(\frac{\beta_1}{2})} \qquad (3\text{-}2)$$

where: $\beta_1 = \lambda' l = \lambda' L' v'$; $v = l / L$; $\gamma_1 = 2\pi v'$; $\bar{x} = x / l$.

$\lambda' = \sqrt{k_a / EA}$; k_a, EA are the axial spring constant of ground and the axial rigidity of the pipeline.

$$\alpha_1 = \frac{1}{1 + (2\pi / \lambda' L')^2} = \frac{1}{1 + (\gamma_1 / \beta_1)^2}$$

$\xi_1(\bar{x})$ will reach maximum value at $\bar{x} = 1/2$

$$\xi_1 = 1 - \frac{\cos(\frac{\gamma_1}{2})}{ch(\frac{\beta_1}{2})} \qquad (3\text{-}3)$$

(2) Analysis in the lateral direction

According to the seismic deformation method, the displacement $v(x)$ of a buried pipeline in the lateral direction must satisfy the equilibrium equation

$$\frac{d^4 v(x)}{dx^4} + \lambda^4 v(x) = \lambda^4 v_G(x) \qquad (4)$$

where: $\lambda = \sqrt[4]{k_b / EI}$; k_b, EI, $v_G(x)$ are the transverse spring constant of ground, the bending rigidity of the pipeline and the seismic ground displacement in the lateral direction, respectively.

The sinusoidal ground displacement (with incident angle $\theta = 0°$), which will cause maximum bending moment at the middle of the segment($x = l/2$) can be expressed

$$v_G(x) = V_G \cos\{\frac{2\pi(x - l/2)}{L}\} \qquad (5)$$

where: L is the wave length, V_G is the lateral displacement amplitude of ground motion at the level of the pipeline.

Based on the assumption of free stress end boundary condition, under the action of the seismic ground displacement expressed in Eq.(5), the bending moment developed in the pipeline segment can be obtained as (solving procedure has been omitted)

$$M(\bar{x}) = \xi_2(\bar{x}) M_0 \qquad (6\text{-}1)$$

where: $\bar{x} = x / l$ $M_0 = EI(\frac{2\pi}{L})^2 \alpha_2 V_G$

$\xi_2(\bar{x})$ is the bending moment modification factor

$$\xi_2(\bar{x}) = -\Big\{\beta\cos(\tfrac{\gamma}{2})\{\cos\beta\bar{x}[\cos\beta sh\beta\bar{x} + \sin\beta ch\beta\bar{x} - sh\beta(\bar{x}-1)] + \sin\beta\bar{x}[-\cos\beta ch\beta\bar{x} + \sin\beta sh\beta\bar{x} + ch\beta(\bar{x}-1)]\} + \gamma\sin(\tfrac{\gamma}{2})\{\cos\beta\bar{x}\sin\beta sh\beta\bar{x} - \sin\beta\bar{x}[\cos\beta sh\beta\bar{x} + sh\beta(\bar{x}-1)]\}\Big\} \Big/ \beta(\sin\beta + sh\beta) + \cos\gamma(\bar{x} - \tfrac{1}{2}) \qquad (6\text{-}2)$$

where: $\beta = \sqrt[4]{k_b/4EI} \times l = \lambda l/\sqrt{2} = \lambda L\nu/\sqrt{2}$; $\nu = l/L$; $\gamma = 2\pi\nu$; $\alpha_2 = \dfrac{1}{1+(2\pi/\lambda L)^4} = \dfrac{1}{1+4(\gamma/\beta)^4}$

$\xi_2(\bar{x})$ will reach maximum value at $\bar{x} = 1/2$

$$\xi_2 = 1 - \frac{2\{\beta\cos(\frac{\gamma}{2})(\sin\frac{\beta}{2}ch\frac{\beta}{2} + \cos\frac{\beta}{2}sh\frac{\beta}{2}) + \gamma\sin\frac{\gamma}{2}\sin\frac{\beta}{2}sh\frac{\beta}{2}\}}{\beta(\sin\beta + sh\beta)} \qquad (6\text{-}3)$$

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3. VALUATION OF EMPIRICAL FORMULAE IN THE GUIDELINE OF CUD

The formulation of the derived formulae of stress modification $\xi_1(x)$ and $\xi_2(x)$ as shown in Eq.(3-2) and Eq.(6-2) is different from that defined in seismic design guidelines for buried pipelines in Japan, but the calculation results of both formulae are the same. However, the expression of the former, namely the new results, is simpler than that of the latter. On the other hand, the guidelines for buried pipelines in Japan did not give formulae of the maximum values for the stress modification factor ξ_1 and ξ_2 of $\xi_1(x)$ and $\xi_2(x)$, because the formulae of $\xi_1(x)$ and $\xi_2(x)$ are quite complicated. This paper derived the formulae of ξ_1 and ξ_2 as shown in Eq.(3-3) and Eq.(6-3), and the formulation is very simple and convenient for hand calculating. In order to simplify the calculation of ξ_1 and ξ_2, the Guideline of CUD of Japan proposed empirical formulae as[4)]

$$\xi_1 = 900L^{-1.8} \qquad \text{Eq.(a)}$$
$$(\lambda' L' = 0.7 \sim 4.7; l/L' = 0.06 \sim 0.35)$$

$$\xi_2 = 1.16\times10^6 L^{-3.8} + 890\lambda^{3.7} \qquad \text{Eq.(b)}$$
$$(\lambda L = 3.6 \sim 25.6; l/L = 0.08 \sim 0.33)$$

$$\xi_3 = 5.31\times10^5 L^{-3.7} + 145\lambda^{2.9} \qquad \text{Eq.(c)}$$
$$(\lambda L = 6.5 \sim 40.3; l/L = 0.08 \sim 0.33)$$

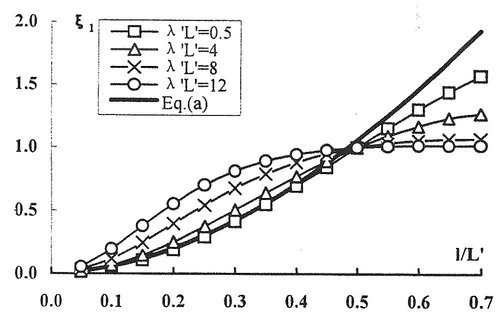

Fig.1 Comparison of axial force modification factor

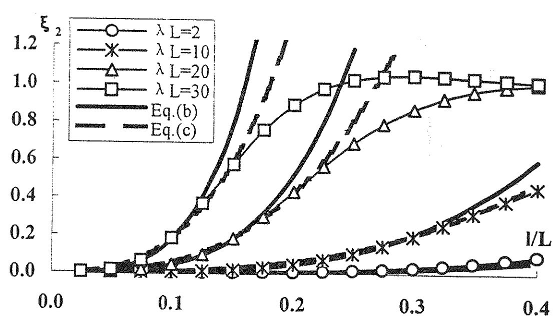

Fig.2 Comparison of moment modification factor

These empirical formulae are inferred from regression analysis of 35 varieties of the actual pipeline's section and ground condition usually applied in construction. The parameters in parenthesis express the region of the pipeline's sections and the ground conditions, and segment length is 30m. The Eq.(b) and Eq.(c) present the moment modification factors for the case of wave propagation in vertical plane and horizontal plane, respectively, so they can be regarded as the same kind of regression formulae in the different parameter region[4]. To check out the empirical formulae, a comparison study between the empirical formulae Eq.(a) (for the case of L=30m), Eq.(b) and Eq.(c) (for the cases of λL=2,10,20,30), and the complete formulae Eq.(3-3) and Eq.(6-3) has been made. The results are shown in **Fig.1** and **Fig.2**.

In the **Fig.1**, it reveals that the Eq.(a) (bold solid line) might fit well with formula Eq.(3-3) in the regression region. The **Fig.2** showed a favorable agreement between the Eq.(b) (bold solid line), Eq.(c) (bold dash line) and the formula Eq.(6-3) in the region of λL<10, but the Eq.(b) and Eq.(c) separated from formula Eq.(6-3) when l/L and λL increase and the difference between the two kind of formulae will increases with increase of $\lambda L(\lambda' L')$ and $l/L(l/L')$. When the parameters exceeded the regression region, the empirical formulae may make significant errors. Therefore special attention should be paid to the applicable region of the empirical formulae. The authors recommend to apply directly the formulae Eq.(3-3) and Eq.(6-3) .

4. CALCULATION OF STRESS AND DEFORMATION CAUSED BY SETTLEMENT DUE TO EARTHQUAKE

The settlement δ due to an earthquake (caused by liquefaction or subsidence) may occur at a distance d from the end of a segment as showed in **Fig.3**. The displacements $v_1(x)$ for region $x<d$ and $v_2(x)$ for region $x>d$ of the buried pipeline in the lateral direction must satisfy the equilibrium equations, respectively.

$$\frac{d^4 v_1(x)}{dx^4}+\lambda_1{}^4 v_1(x)=0 \quad (x<d) \qquad (7\text{-}1)$$

$$\frac{d^4 v_2(x)}{dx^4}+\lambda_2{}^4 v_2(x)=\lambda_2{}^4\delta \quad (x>d) \qquad (7\text{-}2)$$

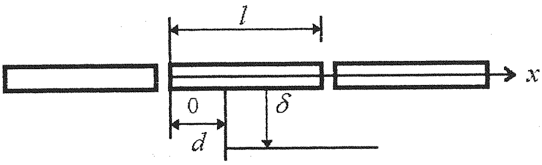

Fig.3 Settlement δ due to an earthquake in a segment

where: $\lambda_{1,2}=\sqrt[4]{k_{b1,2}/EI}$ $k_{b1,2}$ are the transverse spring constants of ground for regions $x<d$ and $x>d$; EI,δ are the bending rigidity of the pipeline and the value of settlement due to an earthquake, respectively.

The free stress at the end boundary conditions and continuos conditions at $x=d$ can be expressed as

for $x=0$, $M_1=0$ and $Q_1=0$

for $x=l$, $M_2=0$ and $Q_2=0$

for $x=d$, $v_1=v_2, \theta_1=\theta_2, M_1=M_2, Q_1=Q_2$ (7-3)

where $\theta_1,\theta_2, Q_1,Q_2$, and M_1,M_2 are angles, shear forces and moments in the pipeline, respectively.

By solving the Eqs. (7-1)~(7-3), the deformation at the joint and the bending moment developed in the pipeline segment can be obtained. For the sake of the complexity of the solutions, here some numerical results will be given as follows (solving procedure has been omitted).

For the case of $k_{b1}=k_{b2}$, the maximum transverse relative displacement and the relative angle at the joint can be expressed as

$$\Delta v=\eta_1\delta \qquad \Delta\theta=\eta_2\,\delta/l \qquad (8)$$

The maximum moment developed in the pipeline can be obtained as

$$M=\eta_3 M_0;\ M_0=e^{-\pi/4}\sin\pi/4\,\frac{EI\beta^2}{l^2}\delta \qquad (9)$$

where M_0 is the maximum moment developed in a pipeline with infinite length under the action of settlement δ. η_1,η_2 and η_3 are the maximum transverse relative displacement factor, the maximum relative angle factor at the joint and the maximum moment modification factor in the segment, respectively. The relations of η_1,η_2 and η_3 with D and β are showed in **Fig.4**, **Fig.5** and **Fig.6**. In the figures, the expressions are as follows.

$$D=\min.\{d/l,\ l-d/l\};\ \beta=\sqrt[4]{k_b/4EI}\times l.$$

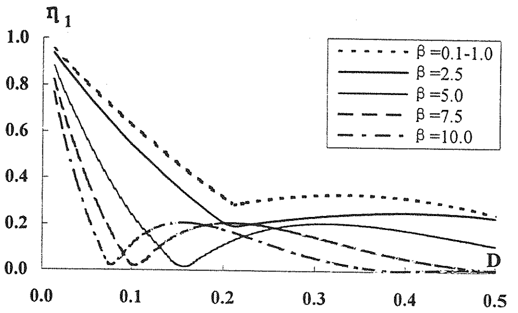

Fig.4 Maximum relative displacement factor η_1 at joint

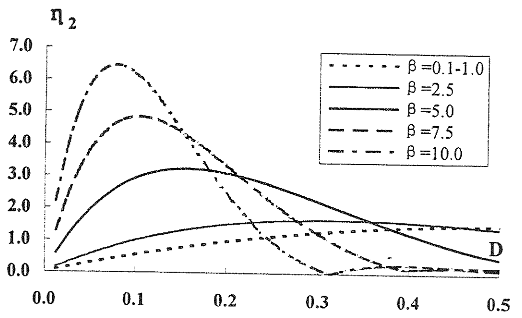

Fig.5 Maximum relative angle factor η_2 at joint

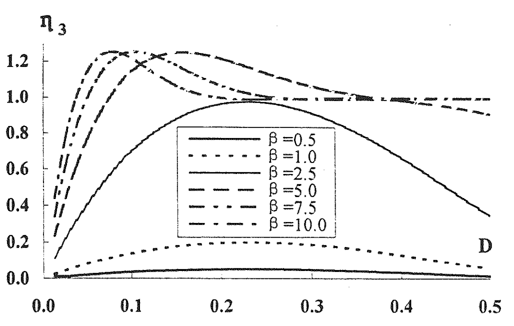

Fig.6 Maximum moment modification factor η_3 in segment

For practical calculation of η_1, η_2 and η_3, we can make useful tables by programming software from the above-mentioned solutions. For the case of $k_{b1} \neq k_{b2}$, namely the transverse spring constants of ground are different for two regions $x < d$ and $x > d$, the solution can also be obtained in the similar way. This solution can consider the case of that, liquefaction or subsidence occurred in an earthquake may cause reduction of the spring constants of ground in the settled side.

5. CONCLUSIONS

(1) In this paper, the authors derived independently formulae to estimate the pipeline's stress and joint's deformation subjected to seismic ground motion in the axial and lateral directions. The formulation of the new results to calculate the stress modification factors are simpler than that defined in seismic design guidelines of Japan.
(2) The empirical formulae applied in The Guideline of CUD may make significant errors when the parameters $\lambda L(\lambda' L')$ and $l/L(l/L')$ exceeded the suitable region. Therefor special attention should be paid to the applicable region of the empirical formulae. In practical application, the author recommends to apply directly the formulae Eq.(3-3) and Eq.(6-3).
(3) In this paper, the authors suggested a calculation procedure to estimate the pipeline's stress and joint's deformation under the action of the settlement due to earthquake. Some numerical results have been showed.

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