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Structural design of buried pipelines for severe earthquakes

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Abstract

In order to realistically assess the seismic risk of a pipeline system, the accurate estimate of the pipe strains which depend upon structural details, pipe material, properties of the surrounding soil, the nature of the propagating wave, etc. is critical. Emphasis in this study, therefore has been placed on the analysis of a structural strain for several types of piping elements unique to the buried pipeline and also the provision of a simplified design formula which can be used practically. The purpose of this study is (a) to define the slippage factor in order to estimate the decrease in pipe strain resulting from the slippage effect, (b) to propose a simplified method to evaluate the plastic deformation of the pipeline for severe earthquakes, and (c) to derive a practical design formula for the structural strains of bent pipes. © 2001 Published by Elsevier Science Ltd.

Keywords: Buried pipeline; Bend; Seismic design; Slippage; Plastic hinge analysis; Strain

1. Introduction

Buried pipelines were damaged at mechanical joints, connections with branches and interconnections with other structures in the 1995 Hyogoken–Nanbu Earthquake in Japan, while arcwelded steel pipelines showed good performance against the severe ground movements.

After this earthquake, many current seismic design guidelines and codes of architectural buildings, civil engineering structures as well as lifeline systems have been revised in order to increase the seismic capability and performance of those structures and their structural systems. A new approach in these revision works [1] in Japan introduced two types of earthquakes which are known as level 1 ground motion and level 2 ground motion, respectively. The former ground motion corresponds to the probable design earthquake (PDE) or the strength level earthquake (SLE), while the latter ground motion is for the contingency design earthquake (CDE) or the ductility level earthquake (DLE).

Since the level 2 ground motion is large enough to produce the plastic deformations in the piping elements, current seismic design approaches which are appropriate to the elastic response cannot be directly applied to the seismic design for the level 2 ground motion. In this situation, there is a need to develop a simplified design formula for buried pipelines which is applicable not only for the level 1 but also for the level 2 ground motions.

The purpose of this study is (a) to define the slippage factor in order to estimate the decrease in pipe strain resulting from the slippage effect, (b) to propose a simplified method to evaluate the plastic deformation of the buried pipeline suffered by severe earthquakes, and (c) to derive a practical design formula for structural strain of the buried bent pipes.

2. Ground motion for a severe earthquake

2.1. Maximum ground displacement

Now we consider a long straight pipeline embedded in an infinite and homogeneous medium which is excited by a traveling seismic wave with a certain incident angle to the pipe axis as shown in Fig. 1. When a seismic wave arrives at the baserock, the surface ground is amplified in accordance with the periodic response characteristics. Based on the seismic analysis [2] of one-dimensional wave propagation in the elastic soil medium with a shear velocity of V_s, the free field displacement U_h can be given by

$$U_h = \frac{2}{\pi^2} S_V T_G \cos\left(\frac{\pi}{2H} z\right) \tag{1}$$

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Nomenclature

U_h	the free field displacement
H	the thickness of the surface ground
T_G	the typical period of the surface ground
z	soil depth to the pipe center
S_V	the response (velocity) spectrum
V_s	shear velocity of the surface ground
V_B	wave velocity of the base rock
ϕ	incident angle
τ_{cr}	the critical shear stress
τ_G	the maximum shear stress acting on the pipe surface
u	the pipe displacement in the longitudinal component
E	Young's modulus of the pipe material
D	pipe outer diameter
t	pipe wall thickness
I	bending moment of the pipe
A	the cross sectional area of the pipe section
β_B	conversion factor for bend
α_0	conversion factor for straight pipe
Δ	relative displacement between the pipe and the free field ground
i	stress concentration factor
n	flexibility factor
h	pipe factor
R	radius of curvature
ψ	bend angle
L	traveling wave length
L_a	apparent traveling wave length along the pipe axis
k	compressional soil stiffness
K_a	the equivalent spring modulus
K_G	the equivalent spring modulus transverse to the pipe axis
q	slippage factor for pipe axial strain
q^*	slippage factor for relative displacement
α	location angle in the bend pipe
ϵ_y	yield strain
ϵ_{cr}	the critical strain
ϵ_p	pipe axial strain
ϵ_B	bend maximum strain
ϵ_G	free field strain
θ_B	bending angle
s_{cr}	the critical passive soil pressure
p	passive soil pressure
M	bending moment
M_p	plastic moment of the pipe

where S_V is the response (velocity) spectrum of the incident earthquake, H is the thickness of the surface ground, z is the soil depth to the pipe center, and T_G is the typical period of the surface ground which is defined by $T_G = 4H/V_s$.

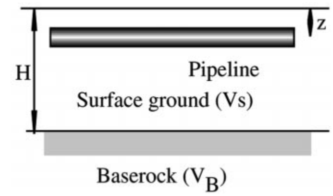

Fig. 1. Schematic example of the surface ground and buried pipeline.

2.2. Maximum ground strain

The motion of the soil particle depends on the type of waves, but can always be resolved into a longitudinal component and a transverse component relative along the wave propagating axis. In general, two types of surface waves, Reyleigh wave and Love wave, correspond to those wave components, while the shear wave propagating from the focal area can also produce a longitudinal motion along the surface ground which results from the phase delay effect. Since there are not any generally accepted methods to define the wave velocity traveling horizontally in the surface ground, the present study adopted the Rayleigh type wave model as the free field ground motion.

Assuming that the sinusoidal wave motion propagates in the horizontal direction, the free field strain is given by

$$\epsilon_G = \frac{2\pi}{L} U_h \tag{2}$$

where L is the wave length.

3. Straight pipe

3.1. Pipe strain

The current studies of seismic response of buried pipelines are usually based on the simplified model of a straight pipe embedded in an infinitive elastic (soil) medium for which the familiar differential equation can be established invoking D'Alembelt's principle with respect to the inertia force, the internal force within the pipe and force proportional to the displacement u of the pipe relative to that of the free field u_G.

The equation for equilibrium of force in the direction longitudinal to the pipe axis is given by

$$\rho A \frac{\partial^2 u}{\partial t^2} - EA \frac{\partial^2 u}{\partial x^2} = K_1 (u_G - u) \tag{3}$$

in which u is the pipe displacement in the longitudinal components; u_G is the apparent free field displacement in the longitudinal component; r and E are mass density and Young's modulus of the pipe material; A is the cross-sectional area of the pipe section; K_1 is the equivalent spring modulus to reflect the soil–structure interaction in the longitudinal direction.

Ignoring the inertia effect for the buried pipeline, the analytical result from Eq. (3) furnishes the pipe strain

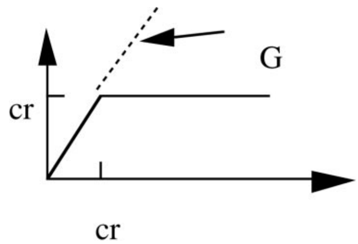

Fig. 2. Shear stress–strain relationship of the soil.

with the conversion factor α_0 as the ratio of the pipe displacement to free field displacement in the same direction:

$$\epsilon_S = \alpha_0 \epsilon_G \tag{4}$$

in which

$$\alpha_0 = \frac{1}{1 + \left(\dfrac{2\pi}{\lambda_1 \cdot L_a} \right)^2}, \quad \lambda_1 = \sqrt{\frac{K_1}{E \cdot A}}$$

where L_a is the apparent traveling wave length along the pipe axis.

3.2. Pipe strain in slippage

The slippage [3] along the interface between the buried pipe and the surrounding soil can take place when the earthquake intensity is severe enough so that the shear stress τ produced in the interface reaches the value τ_{cr} as shown in Fig. 2.

The maximum shear stress acting on the pipe surface can be defined as

$$\tau_G = \frac{2\pi}{L_a} Et\alpha_0 \epsilon_G \tag{5}$$

in which τ is the pipe wall thickness (Fig. 3).

Noting that τ_G in Eq. (5) is deduced without any slippage assumption, the following criteria can be used to determine whether the slippage will or will not take place at least in some portion along the interface.

If $\tau_G < \tau_{cr}$, slippage will not take place.

If $\tau_G \geq \tau_{cr}$, slippage will take place.

This situation can be expressed with the equation for equilibrium in the partial slippage given by

$$EA \frac{d^2 u}{dx^2} + \pi D \tau(x) = 0 \tag{6}$$

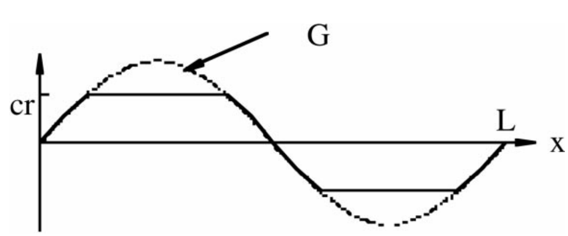

Fig. 3. Shear stress distributions acting on the pipe surface.

where

$$\tau(x) = \left[\begin{array}{ll} \tau_G \sin\left(\dfrac{2\pi}{L} x \right) & \text{in the non} - \text{slippage region} \\ \tau_{cr} & \text{in the slippage region} \end{array} \right.$$

When the sinusoidal wave form is assumed for the free field motion, the maximum pipe strain, when the partial slippage is taking place, can be calculated by

$$\epsilon_S = q\alpha_0 \epsilon_G \tag{7}$$

where q is the slippage factor to estimate the strain reduction effect by slippage given in the following way:

$$\tau_G \geq \tau_{cr}, \quad q = 1 - \cos\xi + \Omega \cdot \left(\frac{\pi}{2} - \xi \right) \sin\xi,$$

$$\xi = \arcsin\left(\frac{\tau_{cr}}{\tau_G} \right), \quad q \leq 1$$

$$\tau_G < \tau_{cr}, \quad q = 1$$

and W is a parameter for analytical simplification of slippage effect, which is recommended to be 1.5. The relative displacement between the soil and the pipe motion is provided by

$$\Delta = (1 - q^* \cdot \alpha_0) \cdot U_h \tag{8}$$

in which the slippage factor q^* is also related to with τ_G/τ_{cr} in the following way:

$$\tau_G \geq \tau_{cr}, \quad q^* = \sin\xi \cdot \left(1 + \frac{\pi^2}{8} - \frac{\xi^2}{2} \right) - \xi \cdot \cos\xi, \quad q^* \leq 1$$

$$\tau_G < \tau_{cr}, \quad q^* = 1$$

3.3. Pipe strain in the plastic region

When the earthquake intensity is severe enough so that the pipe stress exceeds the yielding level of the material, the pipe can produce the plastic strain. Since the pipe deformation is restricted by the surrounding ground motion, the possible maximum pipe strain cannot exceed the ground strain. So the pipe strain in the plastic region can be given by

$$\epsilon_p = \epsilon_G \tag{9}$$

where the above expression neglects the effect of the second stiffness in the stress–strain relationship of the pipe material for its simplification.

4. Bend

When a seismic wave excites the ground, the buried piping structures such as bends experience additional stresses. If such structures are subjected to a seismic wave of apparent wave length L_a propagating in the direction of branch pipe shown in Fig. 4 where the solid line is the ground motion with the

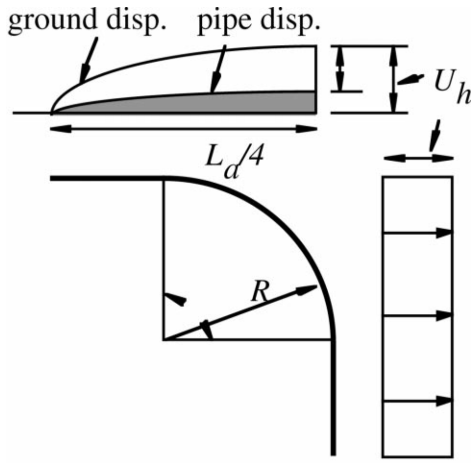

Fig. 4. Bent pipe deformed by forced ground displacement.

maximum amplitude U_h and the shadow edge is pipe displacement, the largest relative displacement Δ will occur at the connection when one of the nodes of the wave is passing the point of a distance $L_a/4$ from the connection.

4.1. Formulation of bent pipe strains in elastic region

4.1.1. Formulation

Analysis of buried bend makes use of the equations for beams on elastic foundations. The maximum stress in the bend turns out to be the bending stress in the bend, calculated by:

$$\sigma_B = i\frac{M}{Z} \tag{10}$$

where M is the maximum bending moment, Z is the pipe section modulus and i is the stress intensification factor. To take into account an effect of stress intensification, the flexibility analysis of a piping system is required, in which the bending moment produces the change in bent angle resulting from that in the radius of curvature through the flexibility factor n, given in the following form:

$$\frac{\Delta\psi}{\psi} = n\frac{MR}{EI} \tag{11}$$

where $\Delta\psi/\psi$ is the change in the bent angle in Fig. 4, R is the radius of curvature, I is the bending moment of the bent pipe.

Let us assume that a bent pipe of an arbitrary angle ψ is subjected to a seismic wave propagating in the direction of one of the straight legs, element (I) in Fig. 5. Because of the simplicity, the bent corner of element (III) is not assumed to be surrounded by any soil. Fig. 5 shows shear forces S_1 and S_2, and bending moments M_1 and M_2.

Given a couple of shear stress S_1 and S_2, and bending moments M_1 and M_2 at both ends of element (III), the bent corner will be deformed, and then produce the resultant rotation of angle θ_B and structural deflection Δ_{S1} and Δ_{S2}, respectively, which can be evaluated, by using Casteliano's theorem in the following way:

$$\theta_B = \psi\frac{nR^2}{EI}\left\{\frac{M_2}{R} + S_1\left(\frac{1-\cos\psi}{\psi} - \sin\psi\right) + S_2\left(\cos\psi - \frac{\sin\psi}{\psi}\right)\right\}$$

$$\Delta_{S1} = \frac{nR^3}{2EI}\left[\frac{2M_2}{R}F_1 + S_1F_2 + S_2(F_3 + F_4)\right]$$

$$\Delta_{S2} = \frac{nR^3}{2EI}\left[\frac{2M_2}{R}G_1 + 2S_1(G_2 + G_3) + 2S_2G_4\right] \tag{12}$$

in which

$$F_1 = 1 - \cos\psi - \psi\sin\psi$$

$$F_2 = 2\psi\sin^2\psi - 4\sin\psi(1-\cos\psi) + \left(1 + \frac{1}{4R^2A}\right)\frac{2\psi - \sin2\psi}{2}$$

$$F_3 = -\psi\sin2\psi + 2\sin^2\psi + 2\cos\psi(1-\cos\psi)$$

$$F_4 = \left(1 + \frac{I}{4R^2A}\right)\cdot\frac{\cos2\psi - 1}{2}$$

$$G_1 = \psi\cos\psi - \sin\psi$$

$$G_2 = \cos\psi - \cos2\psi - \frac{\psi}{2}\sin2\psi$$

$$G_3 = \left(1 + \frac{I}{nR^2A}\right)\cdot\frac{\cos2\psi - 1}{4}$$

$$G_4 = \psi\cos^2\psi - \sin2\psi + \left(1 + \frac{I}{nR^2A}\right)\frac{2\psi + \sin2\psi}{4}$$

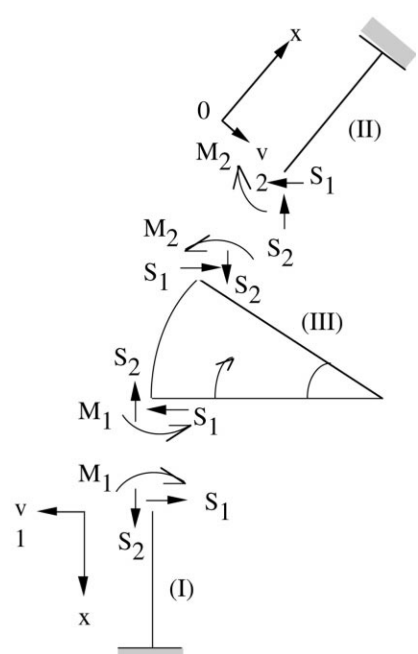

Fig. 5. Applied forces to the bend portion of the buried pipeline.

Then one may find out the boundary conditions at both ends of element (III):

$$v_1(0) = 0, \quad v_2(0) = \Delta_{B1}, \quad \theta_1(0) - \theta_2(0) = \theta_B,$$

$$M_1 = -M_2 + RS_1\sin\psi + RS_2(1 - \cos\psi) \tag{13}$$

where the bending deflection at the pipe end of element (II) in the case of seismic wave incident is parallel to

$$\Delta_{B1} = \Delta_R(\phi) - \frac{L_{a1}}{4}\frac{|S_2|}{AE} - \Delta_{S2} \tag{14}$$

in which L_{a1} is the apparent wave length of the free field motion along the pipe leg of element (I), and the resultant relative displacement can be calculated as

$$\Delta_R(\phi) = |\Delta_1| - |\Delta_2|\cos\psi; \quad -\psi \le \phi \le \pi - \psi \tag{15}$$

in which Δ_1 and Δ_2 are relative displacements of the pipe and the surrounding ground along each pipe leg.

Using Δ_{B1} in Eq. (14), bending moments and shear forces can be expressed by

$$M_1 = 2EI\lambda^2 C_1\Delta_{B1}, \quad M_2 = 2EI\lambda^2 C_2\Delta_{B1}$$

$$S_1 = -2EI\lambda^3 C_1\Delta_{B1}, \quad S_2 = \frac{-2EI\lambda^3\Delta_{B1}(1 + C_1\cos\psi + C_2)}{\sin\psi} \tag{16}$$

where

$$\Delta_{B1} = \frac{\Delta_R(\phi)}{1 + \frac{L_{a1}I\lambda^3}{2A}\left|\frac{1 + C_1\cos\psi + C_2}{\sin\psi}\right| + C_3}, \tag{17}$$

and

$$C_1 = \frac{C_{22}a_1 - C_{12}a_2}{C_{11}C_{22} - C_{21}C_{12}}, \quad C_2 = \frac{C_{11}a_2 - C_{21}a_1}{C_{11}C_{22} - C_{21}C_{12}}$$

$$C_3 = nR^3\left[\frac{2}{R}G_1\lambda^2C_2 - 2\lambda^3C_1(G_2 + G_3) - 2G_4\lambda^3\frac{1 + C_1\cos\phi + C_2}{\sin\psi}\right]$$

$$C_{11} = 1 + 2nR^2\lambda^2\left(1 - 2\cos\psi + \frac{\psi\cos2\psi}{\sin\psi}\right)$$

$$C_{12} = -1 - 2nR^2\lambda^2\left(1 + \frac{\psi}{R\lambda} - \psi\cot\psi\right)$$

$$C_{21} = 1 + R\lambda\left(\cot\psi - \frac{\cos2\psi}{\sin\psi}\right)$$

$$C_{22} = 1 + R\lambda\frac{1 - \cos\psi}{\sin\psi} \tag{18}$$

$$a_1 = -\sin\psi - 2nR^2\lambda^2(\psi\cos\psi - \sin\psi), \quad a_2 = -\lambda R(1 - \cos\psi)$$

$$\lambda = \left(\frac{K_G}{4EI}\right)^{1/4}$$

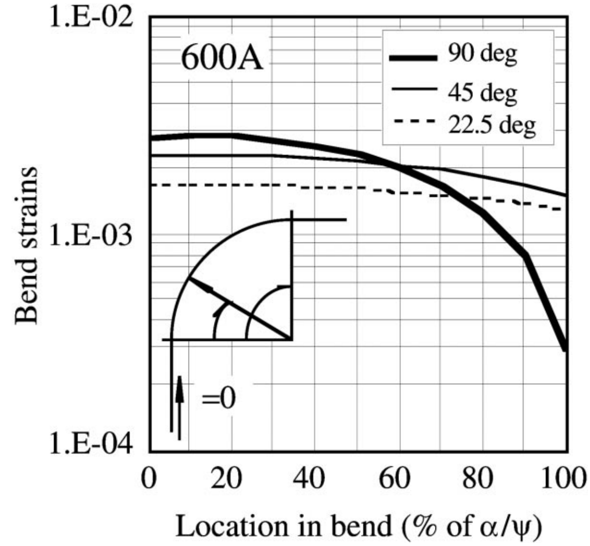

Fig. 6. Bend strain distributions of various bent pipes.

in which K_G is the equivalent spring modulus to reflect the soil interaction in the transverse direction to the pipe axis.

Noting that the bending moment and axial force at any point α along the bent pipe for the incident angle ϕ of seismic wave to the pipe element (I) are given by

$$M(\phi, \alpha) = M_2 - S_1R(\sin\psi - \sin\alpha) - S_2R(\cos\alpha - \cos\psi)$$

$$S(\phi, \alpha) = S_1\sin\alpha - S_2\cos\alpha \tag{19}$$

The structural strain at this point for seismic component incident parallel to the pipe element (I) is calculated by

$$\epsilon_{B1}(\phi, \alpha) = \frac{iD}{2EI}|M(\phi, \alpha)| + \left|\frac{S(\phi, \alpha)}{AE}\right| \tag{20}$$

Combining the structural $\epsilon_{B2}(\phi, \alpha)$ for seismic component incident parallel to the pipe element (II) with $\epsilon_{B1}(\phi, \alpha)$, the resultant structural strain of bent pipe for an incident angle ϕ is given as follows:

$$\epsilon_B(\phi, \alpha) = \epsilon_{B1}(\phi, \alpha) + \epsilon_{B2}(\phi, \alpha) \tag{21}$$

Fig. 6 shows the strain distributions in the bent corner for the various bent pipes which are calculated in Eqs. (20) and (21) for the incident angle $\phi = 0$. It is apparent that the 90° bend shows the maximum strain around 13–15% in the bent corner, while the strains of the 45° and the 22–1/2° bends are less in the location of α/ψ equal to 0–60% but greater in that of α/ψ equal to 60–100% than that of the 90° bend. From these observations, it cold be concluded that the maximum bend strain can be represented by that of the 90° bend for the practical design purpose.

4.1.2. Conditions for the maximum strain of bent pipe

Since the seismic design procedures shown in the previous section seem to be too comprehensive compared to the current design guidelines [4], one may develop a

Table 1
Condition of bent pipe for FEM analysis

Item		Description
(1) FEM code		ABAQUS Ver. 5.7
(2) FEM element		4 nodes shell element
(3) Pipe dimensions	Diameter	610 mm
	Thickness	15.1 mm
	Curvature	3 × Diameter
	Bend angle	90°
(4) Internal pressure		9.1 MPa
(5) Material characteristics	Yield stress	540 N/mm^2
	Hardening coefficient	21 N/mm^2

simplified design formula by fixing the conditions to produce the maximum structural strain of bent pipe.

Since the 90° bent pipe is one of the typical bends in the actual piping configurations, numerical calculations were done for the dilatational wave propagation along the pipe axis. Then the maximum structural strain is estimated at the bent corner of $\alpha = 12°$. Based on these observations, one may insert $\psi = 90$, $\phi = 0$, $\alpha = 12$ to Eqs. (15)–(17) with the minor arrangements of $\sin\alpha \approx 0.2$ and $\cos\alpha \approx 1.0$, to obtain the following simplified formula:

$$\epsilon_B = \beta_B \Delta \tag{22}$$

where β_B is the conversion factor from the relative displacement to the structural strain of bent pipe.

$$\beta_B = \frac{2iA\lambda^2 D|(5 + R\lambda)b_1| + 4\lambda^3 I|5(1 + b_2) - b_1|}{10A + 5LI\lambda^3(1 + b_2) + 10Ab_3} \tag{23}$$

in which

$$b_1 = -\frac{1 + 2R\lambda + (\pi - 2)nR^2\lambda^2}{(1 + R\lambda)\{2 + \pi nR\lambda + (4 - \pi)nR^2\lambda^2\}}$$

$$b_2 = -\frac{1 - 2nR^2\lambda^2 - (4 - \pi)nR^3\lambda^3}{(1 + R\lambda)\{2 + \pi nR\lambda + (4 - \pi)nR^2\lambda^2\}}$$

$$b_3 = nR^3\lambda^3\left\{\frac{\pi}{2} + \frac{\pi I}{2nAR^2} + \left(1 - \frac{I}{nAR^2}\right)b_1 + \left(\frac{2}{R\lambda} + \frac{\pi}{2} + \frac{\pi I}{2nAR^2}\right)b_2\right\}$$

4.2. Plastic analysis of bent pipe

4.2.1. FEM analysis

When a pipeline is subjected to a severe earthquake, the relative displacement between the pipe and surrounding soil will be large enough to cause a plastic strain in the bent pipe. Seismic design formulae of Eqs. (22) and (23), however, are not applied for this situation, because these equations are developed by the flexibility analysis of the elastic piping system of bent portion.

In order to develop the practical design formula applicable to bent pipe in the plastic region, the finite element analysis is adopted with ABAQUS, the applicability of which was assessed by comparing the numerical calculations [5] with the experimental results [7] of full-scale bent pipes through the numerical conditions given in Table 1 and Fig. 7.

The moment–curvature relationships are compared with the experimental results and FEM ones in Fig. 8, while the strain distributions along the pipe surface are compared in Fig. 9. These figures indicate that the FEM analysis can provide a good applicability to predict the actual behavior of bent pipes under plastic deformations.

Based on this result, one may develop the design formula for the plastic deformation of bent pipes, which is compatible to the result of FEM analysis.

The accuracy of the simplified design formula of Eq. (22) is assess in Fig. 10 where the analytical results (solid line) given by Eq. (22) are compared with FEM calculations (dot points). The numerical conditions of Fig. 10 is summarized with the diameter = 610 mm, thickness = 15.1 mm and the curvature = three times pipe diameter and the seismic design load follows the guidelines of Japan Gas Association (JGA) whose details are described in Section 4.

It is apparent that both results show comparatively good agreement and the simplified formula provides the slightly larger strain estimate except for the strain at the typical period of 0.3 s, while both results are under the critical strain which is equal to the plastic strain calculated from the plastic moment of the pipe.

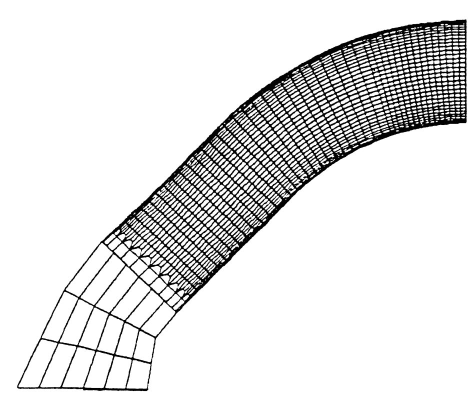

Fig. 7. FEM modeling of the bent portion.

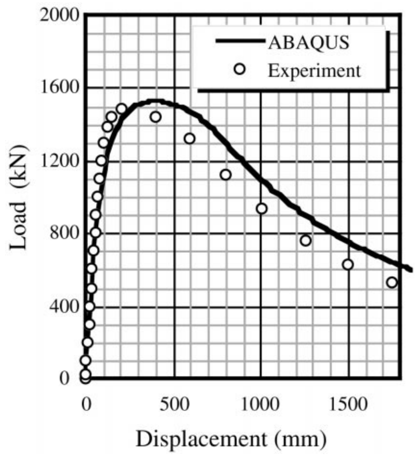

Fig. 8. Moment and curvature relationship of the bent portion.

It should be noted that the above discussion is valid only for the 600A diameter bend as well as for in the elastic region. In order to confirm the greater strains for the 90° end, the same calculations must be carried out for the smaller diameter bend.

Two types of bends, 90 and 45°, of a diameter 300A are numerically compared which can provide the maximum bend strain in the plastic region. As shown in Fig. 11, the 90° bend produces relatively large strains for all the typical periods of the ground. From this observation, the following discussions on plastic behaviors of bent pipe are limited to the 90° bend.

4.2.2. Plastic hinge modeling

When the pipeline is deformed by large ground motions, a bend corner behaves as a fixed point, so that the large relative displacement must be absorbed by the rotation of bent pipe and the deflection of the connected pipe. If the relative displacement is large enough to produce a plastic hinge [6], the bent corner can rotate with plastic moment M_p as shown in Fig. 12(1). In case of more excessive relative deformation at the bent corner, another plastic hinge will be made at the connected portion given in Fig. 12(2).

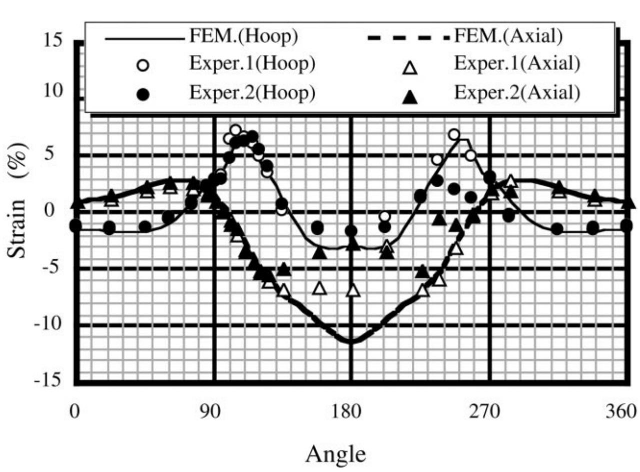

Fig. 9. Stress distributions along the pipe surface.

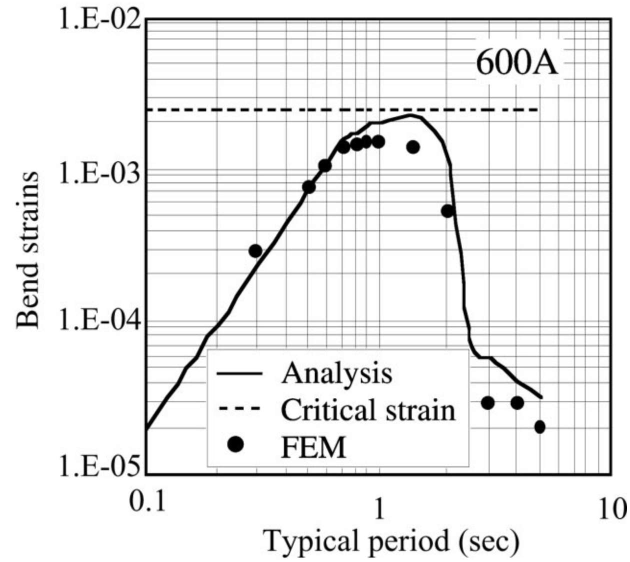

Fig. 10. Comparison between analysis and FEM calculations.

Steel pipe used for high-pressure gas pipelines shows the bi-linear stress–strain curve. After yielding, the pipe can behave as a beam which can rotate with plastic moment M_p.

For the simplified analytical formulations, one may introduce the following assumptions:

1. a bent pipe and its connected portion (W_1 or W_2 in Fig. 12) behave as beam loaded by soil reaction force, while the other portion far from the bent corner moves coincidently with a ground displacement U_h;
2. the bent corner is modeled as a fixed point which can rotate with plastic moment M_p.

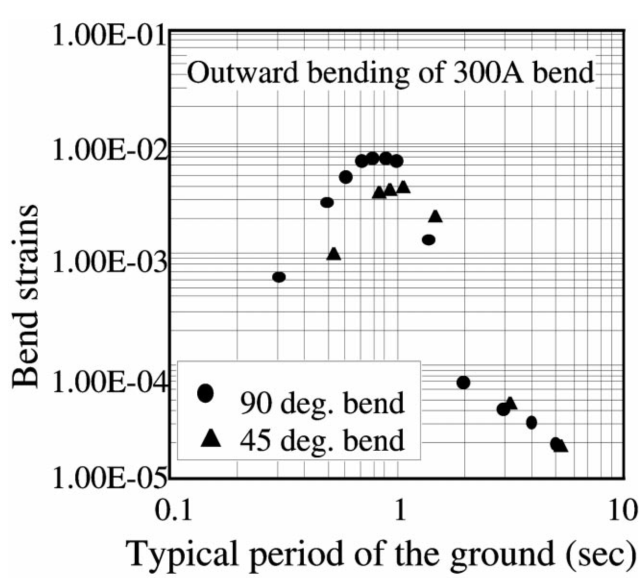

Fig. 11. Comparison between the 90 and 45° bends.

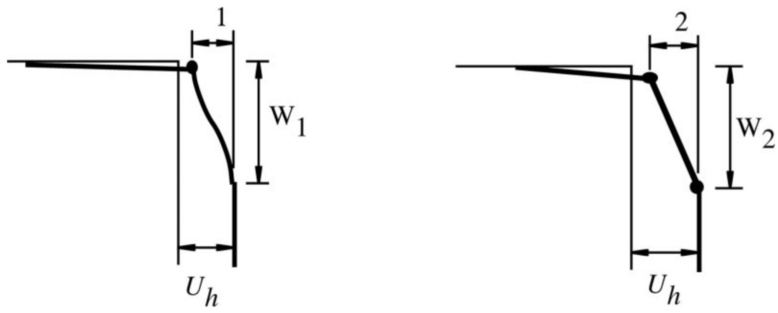

Fig. 12. Plastic hinge formation at the bend portion.

The small ground movement produces the elastically linear soil pressure to the pipe, while, after the soil pressure exceeds the critical value of s_{cr} as shown in Fig. 13, the soil pressure is limited to be equal to the passive soil pressure. The soil pressure p per unit length is given with a pipe diameter D by

$$p = Ds_{cr} \tag{24}$$

In general, the equation of motion of the buried pipe can be expressed with a bending rigidity EI of the pipe:

$$EI\frac{d^4w}{dx^4} \quad 0 \leq x \leq W \tag{25}$$

Fig. 14 shows the model of bend portion in which the bent pipe corner is located at the point ($x = 0$), and the connected pipe is stretched up to the point ($x = W$).

When the first plastic hinge is formed at the bent corner, the boundary conditions are given in the following way [5]:

$$x = 0, \quad w(0) = 0, \quad \frac{dw(0)}{dx} - 0;$$

$$x = W, \quad w(W) = \Delta, \quad \frac{dw(l)}{dx} = 0$$

Solving Eq. (25) with these boundary conditions, the pipe deflection and its length to produce a plastic hinge at the bent corner are estimated as

$$\delta_{p1} = \frac{3}{8}\left(\frac{M_p^2}{EIp}\right), \quad W_1 = \sqrt{3}\sqrt{\frac{M_p}{p}} \tag{26}$$

The pipe deflection and its length when the second plastic hinge appears at the point of $x = W$ are expressed as

$$\delta_{p2} = \frac{10}{3}\left(\frac{M_p^2}{EIp}\right), \quad W_2 = 2\sqrt{\frac{M_p}{p}} \tag{27}$$

with the boundary conditions of

$$x = 0 \quad w(0) = 0 \quad M(0) = -M_p\,;$$

$$x = W \quad w(W) = \Delta \quad \frac{dw(l)}{dx} = 0$$

For instance, the pipe deflections of δ_{p1} and δ_{p2} for the pipe diameter 300A shown in Table 2 are evaluated to be 1.3 and 1.2 cm, respectively, which means that the first plastic hinge is formed at the relative displacement of 1.3 cm, while the second plastic hinge is at that of 12 cm.

4.2.3. Simplified strain estimate by equivalent stiffness method

In order to maintain a conservative estimation of bent pipe strains, a single plastic hinge model of Fig. 12(1) is adopted hereunder. Therefore, the stretch of pipe length at the bend corner is selected from Eq. (26) as

$$W = \sqrt{\frac{3M_p}{p}}$$

Once the relative displacement Δ is given to the bent corner, the deformed bent angle θ can be approximated with the equation of

$$\theta = \arctan\left(\frac{\Delta}{W}\right) \tag{28}$$

If an approximation technique can be applied to estimate

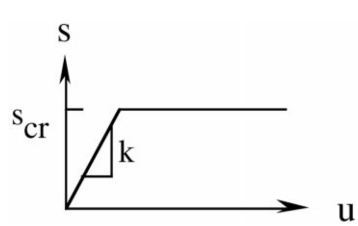

Fig. 13. Soil reaction characteristics.

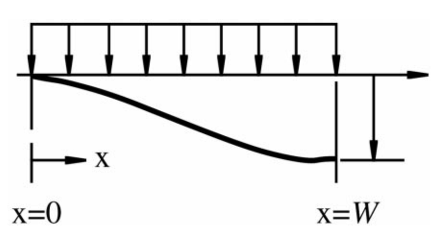

Fig. 14. Structural model for bent pipe making plastic hinges.

Table 2
Numerical conditions of bent pipes

Item	Unit	100A	150A	300A
Diameter (D)	mm	114.3	165.2	318.5
Thickness (t)	mm	4.5	5.0	6.9
Radius of curvature (R/D)		1.5	1.5	3
Cross-sectional rigidity (I)	mm^4	2.34×10^6	8.08×10^6	8.2×10^7
Young's modulus (E)	N/mm^2	2.1×10^5	2.1×10^5	2.1×10^5
Yield stress (s_y)	N/mm^2	252	252	335
Plastic moment (M_p)	Nmm	1.37×10^7	3.23×10^7	2.24×10^8
Soil restriction force (S_{cr})	N/mm^2	0.26	0.26	0.26
Deflection—single hinge (δ_{p1})	mm	4.8	5.4	13.2
Deflection—double hinge (δ_{p2})	mm	42.7	47.9	117.8

the deformed bent angle and the maximum strain in the plastic region with equivalent coefficients β_1 and β_2, the following relationships are obtained:

$$\theta = \beta_1 \psi n \frac{MR}{EI}, \quad \epsilon_B = \beta_2 i \frac{M}{EI} \frac{D}{2} \tag{29}$$

Using Eqs. (28) and (29), a new design formula to estimate the structural strain of the bent corner from the relative displacement Δ with the equivalent coefficient C_B in the following way:

$$\epsilon_B = C_B \frac{iD}{2\psi n R} \arctan\left(\frac{\Delta}{W}\right) \tag{30}$$

where the equivalent coefficient C_B can be evaluated through the comparison with the result of Eq. (30) and the FEM numerical results given in the following section. The value of $C_B = 3$ is recommended for current classes of high-pressure gas pipelines.

5. Numerical study

Numerical calculations are carried out with the design conditions used in the Japan Gas Association (JGA) as shown in Table 2, in which the soil restriction force, S_{cr}, is obtained through the experiments of buried pipelines done by JGA [7]. Earthquake excitation at the baserock is furnished by the spectral velocity [4] given in Fig. 15, while the horizontally traveling seismic wave is defined as Rayleigh-type surface wave with its dispersion curve [5] shown in Fig. 16.

Fig. 17 shows the comparisons of the maximum structural strains of the bends for various ground conditions between the simplified design formula of Eq. (30) (the solid line) and FEM calculations (dotted symbol), while the brokem line shows the plastic strain of each pipe material. According to these figures, both results for the diameters of 100A, 150A and 300A show good agreement.

Fig. 17(1)–(3) illustrates typical trends: (1) smaller diameter bend shows greater strain, while larger diameter bend might be kept in the elastic region even in a severe earthquake as shown in Fig. 10; (2) the maximum strain of the bends generally used in Japan will be less than 3%.

6. Conclusion

This study was aimed to furnish the simplified design formula of structural strains of several types of piping elements unique to the buried pipeline. The following four

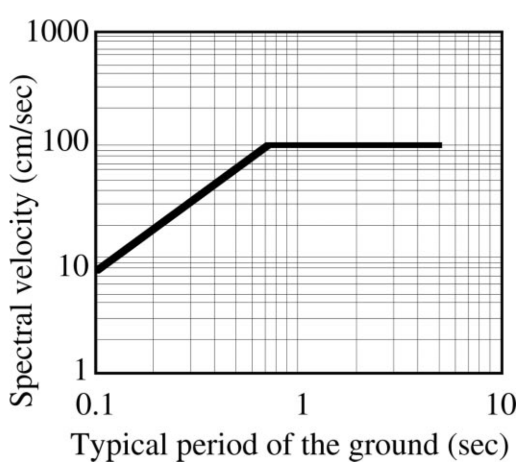

Fig. 15. Spectral curve for the seismic design of buried pipelines given by JGA [4].

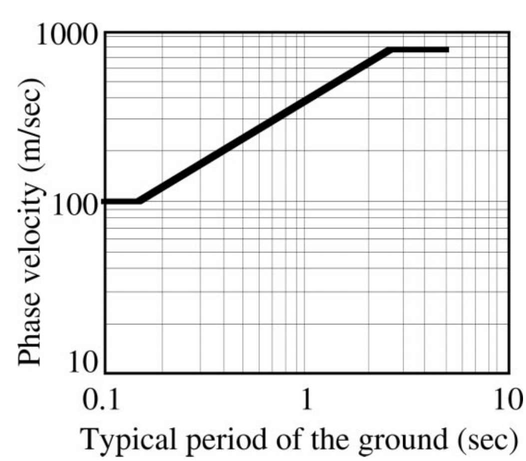

Fig. 16. Dispersion curve of the surface ground given by JGA [4].

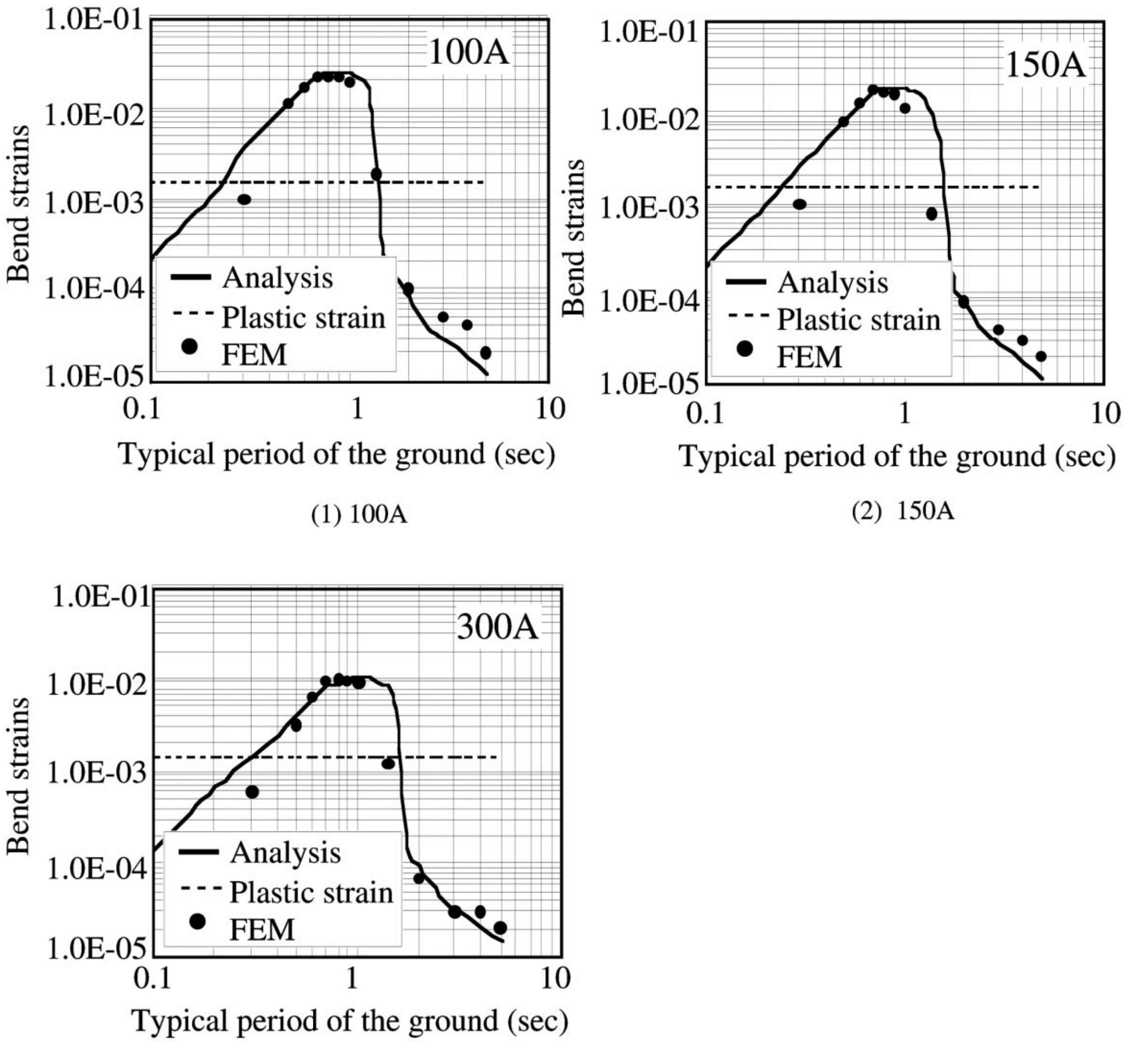

Fig. 17. The maximum structural strains of the bend portions.

items can be summarized as follows.

1. Not only comprehensive analytical formula but also simplified design formula for bent pipes are developed for large seismic ground motions.
2. Slippage factors are defined in order to estimate the decrease of pipe strain resulting from the slippage effect and to evaluate the bent strain which is proportional to the relative displacement between the pipe and its surrounding soil.
3. Plastic hinge model, which is introduced to evaluate the structural strains of bent pipes suffered by a sever earthquake, shows good accuracy with the FEM calculations.
4. Simplified design formula to estimate the maximum structural strains of buried bent pipes can be formulated in which one equation (Eq. (22)) is applicable for Level 1 earthquake, while the other (Eq. (30)) is for the Level 2 earthquake.

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