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A SIMPLIFIED ESTIMATION METHOD OF ELASTO-PLASTIC DEFORMATIONS OF BURIED PIPELINES CAUSED BY LATERAL SPREADING DUE TO LIQUEFACTION

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SUMMARY

Practical method to estimate the structural strains of buried pipelines under lateral spreading in the liquefied ground is proposed. Two different patterns of ground deformations at slope and revetment are selected as the typical lateral spreading modes. The shell/beam hybrid model is used to analyse the inelastic behaviour of buried pipes, using the FEM code of ABAQUS. For the practical formulation conforming to those FEM results, the plastic limit analysis method is adopted to deal with the plastic behaviours of pipeline systems. Finally, a simplified design formula is deduced to evaluate the deflection angle of the bend corner in the pipeline system, from which the structural strain can be estimated with the relationship between the maximum structural strain and deflection angle of the bend.

INTRODUCTION

Liquefaction hazard is observed along the revetment of the reclamation area or alluvial grounds with a slight slope near riversides.

Lateral spreading in the liquefied ground often causes several meters of large ground displacements, so that the pipeline crossing these areas may be deformed inelastically or might be buckled or torn out. There are many theoretical and numerical techniques to evaluate the inelastic behaviours of the pipeline and its bending portions, while there are not any simplified design formula to provide the non-linear structural strain or its equivalent value such as a deflected angle.

The proposed method1) is based on the plastic limit analysis5), while the applicability of the modelling and its analytical technique is assessed for the simplified design formula with FEM analysis3) which was also verified with the full-scale test results of bend pipes. The simplified design formula developed herein can provide the deflection angle of bend pipe which is effective as a practical measure to estimate the large inelastic structural behaviours of the buried pipelines and their geometrical elements. Numerical study is devoted to assessing the applicability of the proposed method.

2. LIQUEFACTION HAZARD

2.1 Typical Patterns of Ground Movement by Lateral Spreading

Many pipelines might be installed in a reclamation area or along the shoreline, while major trunk lines basically cannot escape the river crossing or geotechnically hazardous grounds. In the liquefaction hazard area, a certain

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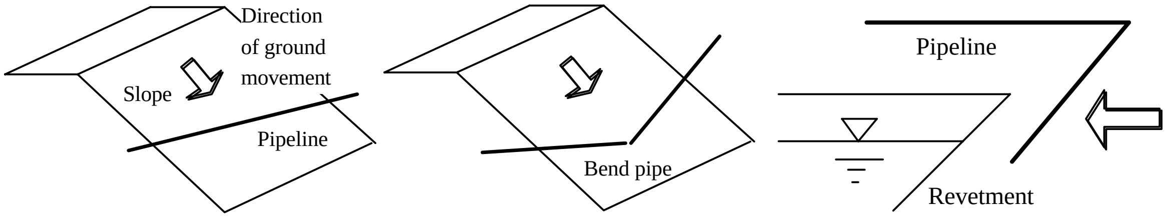
stretch of the pipeline is often installed in the slope area, in which a straight pipe or bend corner may experience a large ground movement caused by lateral spreading of the liquefied ground as shown in Fig.1. One may also have a pipeline to be parallely installed along the revetment, where the liquefaction-induced ground movement causes large bending deflection of bend pipe especially in the corner portion..



(1)Straight pipe (2)Bend in the slope portion (3)Bend at the revetment

Fig.1 Typical patterns of ground movement under lateral spreading resulting from liquefaction hazard.

The 1995 Hyogoken-Nanbu Earthquake and other recent events provide many information on the ground displacement for various geotechnical conditions. Since there are many varieties in the size of the liquefied ground, certain values are selected as an approximate estimation of the typical size of the liquefied ground in this study; 20m, 100m and 200m.

One may also adopt two ground movement modes, slope type and revetment type, as the typical lateral spreading resulting from the liquefaction hazard. Although it is difficult to estimate the ground displacement of both types, there are proposed some simple formulae as shown in the following way.

(1)The ground displacement in the slope area

Hamada and Wakamatsu[2)] propose the approximate formula to predict the maximum ground displacement in the slope area which is liquefied during the earthquake in the following way.

$$\delta_{max} = \frac{C \cdot \sqrt{H} \cdot \theta}{\overline{N}} \tag{1}$$

where

δ_{max} : the maximum ground displacement (m);
C : parameter to predict the ground displacement, a value of 15 to be recommended;
H : the thickness of the ground (m) which is in the liquefaction;
θ : the angle of the slope (%) which is estimated at the surface of the ground; and
$\overline{N}$: the modified *SPT* value which is given by

$$\overline{N} = \frac{1.7 \cdot N}{\sigma_v' + 0.7}$$

and N and σ'_v are the actual SPT value of the site and the effective vertical soil stress of the ground, respectively.

(2)The ground displacement in the revetment

Based on the observation and empirical results of the 1995 Hyogoken-Nanbu Earthquake, the approximate formula to predict the maximum ground displacement at the revetment is proposed by Iai[4)]

$$\delta_{max} = \alpha \cdot H \tag{2}$$

where H and α are the height of the revetment (m) and a parameter which is recommended by Iai[4)] for each type of the revetment.

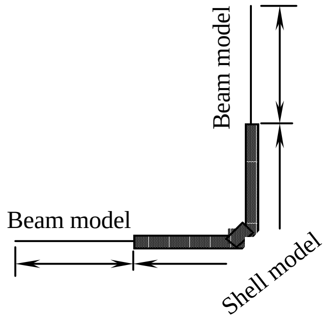


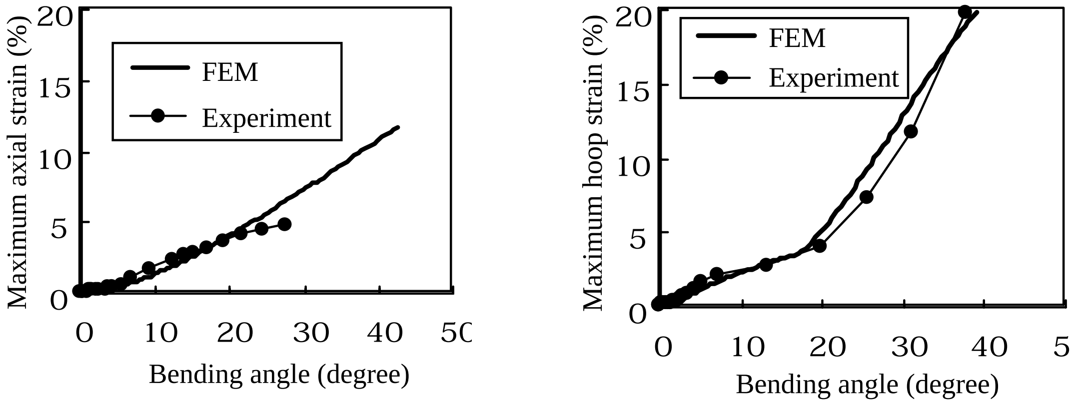
Fig.2 Shell-beam hybrid model of pipe segment with a bend

2.2 FEM Analysis of Bend Pipes for Various Ground Displacement Patterns

2.2.1FEM Analysis compared with experimental results

When a large ground displacement is applied to buried pipelines, inelastic behaviours of pipe material and soil-pipe interaction must be taken into consideration. FEM analysis technique is used to estimate these inelastic structural behaviour. FEM code of ABAQUS is adopted herein, where a shell/beam hybrid model as shown in Fig.2 is introduced. The applicability of this modeling is assessed with the experimental result of the full-scale tests of bend pipes, with which inward and outward bending tests[3)] given in Table 1 are conducted. The bend portion and its some stretch of straight pipe portion are modeled with 4 nodes shell elements and others are formed with beam elements, while the stress and strain curve of pipe material is also modeled with the data of Table 1. Fig.3 shows the relationship between the bending angle and axial and hoop strains of the non-buried bend pipe, in which the bending angle of bend pipe is defined as the tangential angle at the connected portion of bend and straight pipe. Both results of FEM analysis and experiments show good coincidence up to 28 degree for outward bending and 40 degree and the more for inward bending. This difference between the outward and inward bending suggests that the flexibility of bend pipe is more remarkable in the inward bending than in the outward bending.

If the bending angle of bend pipe is estimated, one may obtain the maximum strain from the bending angle through the relationship between the bending angle and maximum strain of Fig.3.



(1) Outward bending (2) Inward bending

Fig.3 Numerical results of the maximum strain and bending angle comparing with the experiments.

Table 1 Numerical conditions (1)

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 x Diameter
	Bend angle	90 degree
(4)Internal pressure		9.1 MPa
(5)Material characteristics	Yield stress	540 N/mm^2
	Hardening coeff.	21 N/mm^2

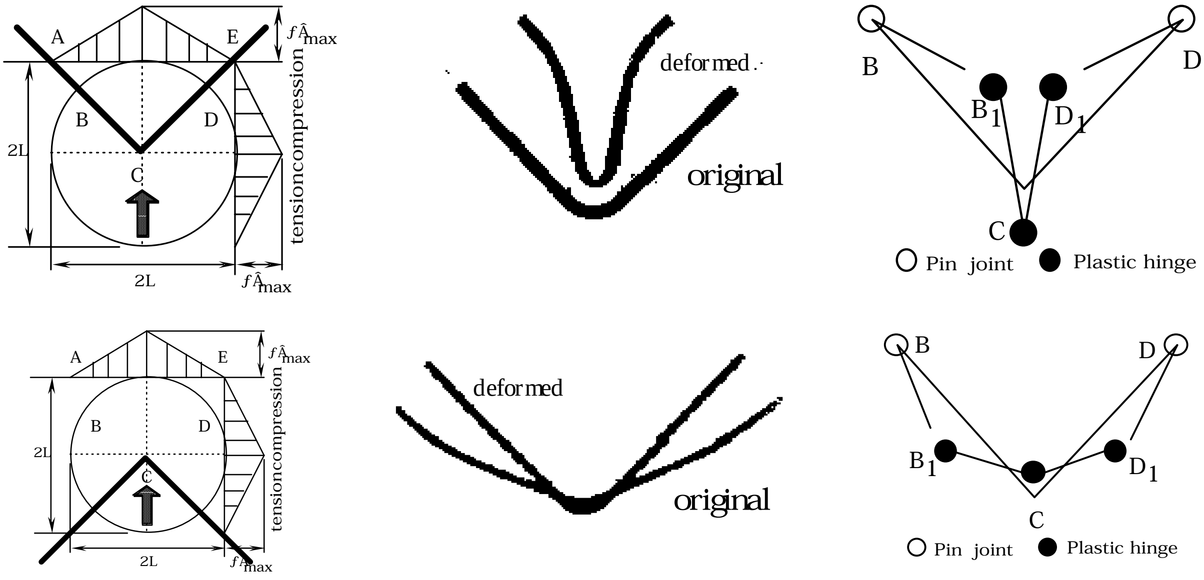
Table 2 Numerical conditions (2)

ITEM	DESCRIPTION
Parameter γ for moment of bend pipe	1.107 (inward) 1.527 (outward)
Length of liquefaction area	200 m
Maximum ground displacement	7 m
Critical soil reaction forces per unit length s_{cr}	0.26 N/mm^2

2.2.2 Bend pipe deformations with plastic hinges under lateral spreading

(1)Slope type

Fig.5(1) shows the analytical conditions of bend pipe installed in the liquefied ground of the slope area. The maximum ground movement is δ_{max}, and the ground strain is assumed to be constant over the liquefied area. As shown in Fig.5(1), these two pipe configurations generate typical pipe deformations; inward bending(left-hand side) and outward bending(right-hand side). Fig.5(2) expresses the results of FEM analysis, which suggests the possibility of plastic hinge formations at three points near the bend. Based on this observation, plastic hinge models as shown in Fig.5(3) are introduced in this analysis. The points B_1 and D_1 are located in the vicinity of bend, while the distance of B_1C and D_1C are derived in the following section.

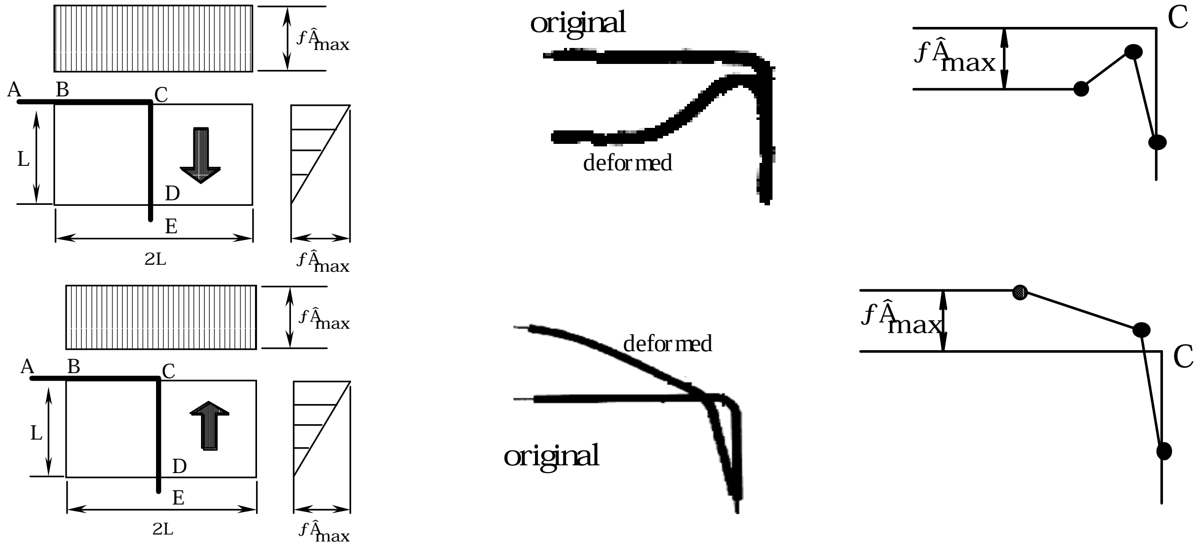


(1)Analytical conditions (2)FEM simulated results (3)Plastic hinge models

Fig.5 Structural models for bend pipe in the slope area.

(2)Revetment type

Fig.6(1) shows the analytical conditions of bend pipe installed in the liquefied ground along the shoreline. As shown in Fig.6(2), these two pipe configurations generate typical pipe deformations; inward bending(left-hand side) and outward bending (right-hand side). Based on this observation of FEM results of Fig.6(2), plastic hinge models as shown in Fig.6(3) are also introduced in this analysis.



(1)Analytical conditions (2)FEM simulated results (3)Plastic hinge models

Fig.6 Structural models for bend pipe along the shoreline.

3. PRACTICAL FORMULATIONS

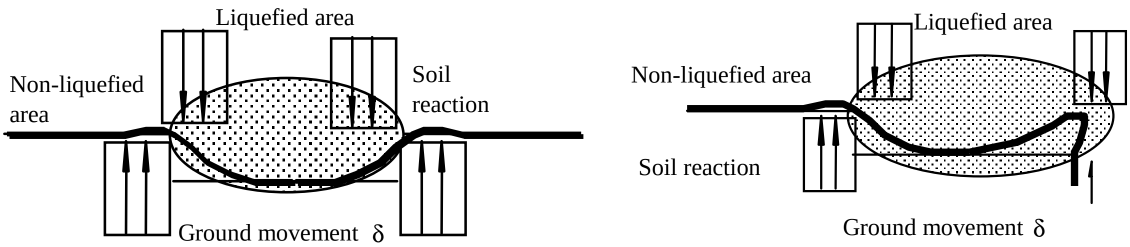
3.1 Plastic Limit Analysis

3.1.1 General Formulation

When a pipeline passes through the liquefied area as shown in Fig.7(1), the most severe relative displacement occurs at the liquefied and non-liquefied boundary area. Since the bend corner, on the other hand, installed at the liquefied area as shown in Fig.7(2) behaves as a fixed point, the large relative displacement can also initiate from the bend portion. For the simplified analytical formulation, one may introduce the following assumptions;

(1)a pipeline near the non-liquefied ground behaves as a beam loaded by soil reaction force, while the other pipe portion moves coincidently with a ground displacement.

(2)the point at which the pipe moves coincidently with a ground displacement is modeled as a fixed point which is, however, movable perpendicularly to the pipe axis up to the ground displacement.



(1)Pipe crossing boundary (2)Bend portion

Fig.7 Analytical models of buried pipelines passing through the liquefied ground.

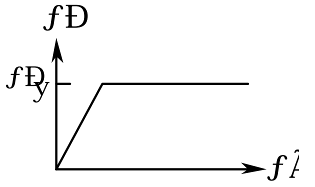


Fig.8 Stress-strain curve of steel pipe.

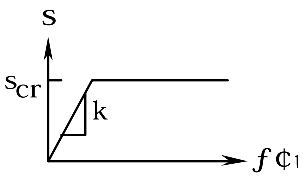
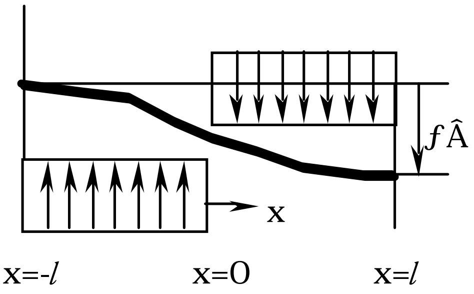
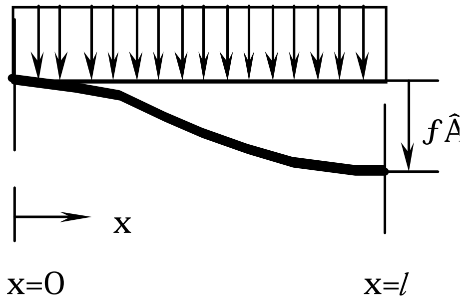


Fig.9 Soil reaction characteristics.



(1)Applying forces at the liquefaction boundary.



(2)Applying forces at the bend portion.

Fig.10 Structural models for pipe beam analysi

Steel pipe shows the bi-linear stress-strain curve as shown in Fig.8. After yielding, the pipe can behave as a beam which can rotate with plastic moment M_p.

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.9, the soil pressure is limitted to be equal to the passive soil pressure. The soil pressure p per unit length is given with a pipe diameter D by

$$p = D s_{cr} \qquad (3)$$

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

$$EI\frac{d^4w}{dx^4} = p \qquad 0 \le x \le l \qquad (4)$$

(1)Pipe crossing boundary model

Fig.10(1) shows the model of pipe crossing boundary, in which the boundary condition is given in the following;

$$x = 0\ ,\ w(0) = \frac{\delta}{2}\ ,\ \frac{d^2w(0)}{dx^2} = 0\ ;\ \ x = l\ ,\ w(l) = \delta\ ,\ \frac{dw(l)}{dx} = 0 \qquad (5)$$

When the end moment at the fixed point reaches the plastic moment, the pipe displacement and its interval of both ends are, respectively, given by

$$\delta_p = \frac{5}{3}\left(\frac{M_p^2}{EIp}\right)\ ,\quad l_p = 2\,l = 2\sqrt{2}\sqrt{\frac{M_p}{p}} \qquad (6)$$

2)Bend portion model

The bend portion model in Fig.10(2) follows the equation (2) , in which two plastic hinges are generated accordingly to the progressive ground displacements.

The pipe displacement and its interval of both ends when the first hinge occurs at *x=0* are given by

$$\delta_{p1} = \frac{3}{8}\left(\frac{M_p^2}{EIp}\right) \quad , \quad l_{p1} = \sqrt{3}\sqrt{\frac{M_p}{p}} \tag{7}$$

with the boundary conditions of $x = 0\,,\ w(0) = 0\ ,\ \frac{dw(0)}{dx} = 0\ ;\ x = l\ ,\ w(l) = \delta\ ,\ \frac{dw(l)}{dx} = 0$ (8)

The pipe displacement and its interval of both ends at the second hinge appearing at $x=l$ is expressed as

$$\delta_{p2} = \frac{10}{3}\left(\frac{(\gamma M_p)^2}{EIp}\right) \quad , \quad l_{p2} = 2\sqrt{\frac{\gamma M_p}{p}} \tag{9}$$

with the boundary conditions of $x = 0 \quad w(0) = 0 \quad M(0) = -M_p \quad ; \quad x = l \quad w(l) = \delta \quad \frac{dw(l)}{dx} = 0$ (10)

3.1.2Formulation for Straight Pipeline

Using the results of Section 3.1.1, the pipe deflection angle under large ground displacement is given for elastic and plastic conditions, respectively. Fig.11 shows two typical models of straight pipe crossing the liquefied area. The pipe deflection angles for both cases are estimated at the liquefied and non-liquefied boundary point A in Fig.11.

(1)Elastic range of $\delta < \Delta_{cr}$

The pipe deflection angle is given by

$$\theta_c = \delta \cdot \lambda \tag{11}$$

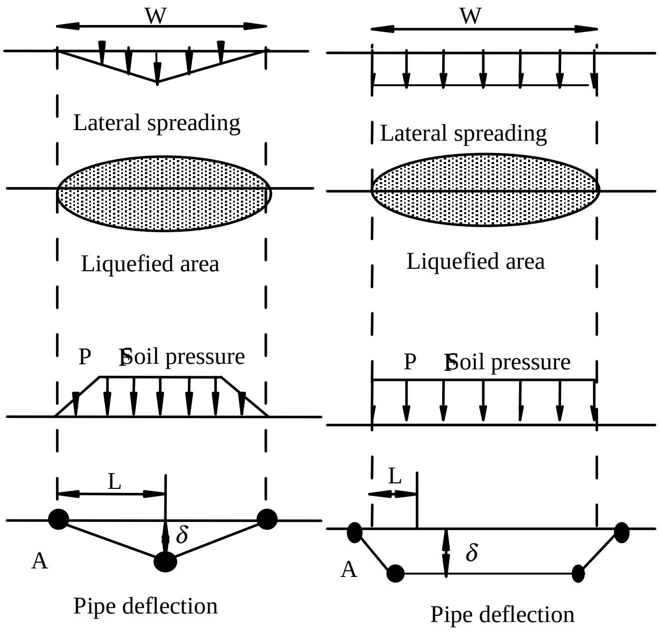
where

$$\Delta_{cr} = \frac{5}{3}\left(\frac{M_p^2}{EIp}\right) \quad , \quad \lambda = \sqrt[4]{\frac{\boldsymbol{K}}{\boldsymbol{4}EI}} \tag{12}$$

(2)Plastic range of $\delta > \Delta_{cr}$

The pipe deflection angle is given by

$$\theta_c = arctan\left(\frac{\delta}{L}\right) \tag{13}$$



(1)Triangular soil distribution. (2)Rectangular soil distribution.

Fig.11 Straight pipe deflections under lateral spreading

with the intervals of $L = \frac{W}{2}$ for triangular soil distribution and $L = 2\sqrt{\frac{2M_p}{p}}$ for rectangular soil distribution

3.1.3Formulation for Bend Pipes

The numerical results of FEM analysis in the section 2.2.2 express that the plastic deflection of bend portion can be estimated with three-plastic-hinge models. Fig.12 is a general configuration of bend pipe deflection with three plastic hinges when a large ground displacement in the liquefied area makes δ_A and δ_B for pipe segments CA and CB. Since the original angle of the bend is 2α and the angle of the deformed bend is $2\theta_y$, the deflected angle of the bend pipe is given as the difference of these angles.

$$\theta_C = 2 \cdot \left|\theta_y - \alpha\right| \tag{14}$$

in which the deflected angle θ_y is derived from the following way.

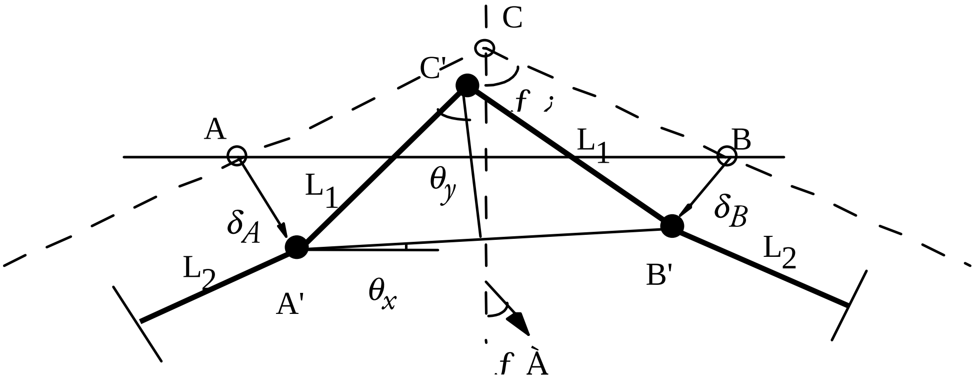


Fig.12 Bend pipe deformation with three plastic hinges.

The ground displacements at the points A and B are given with the directional angle β of the ground movement:

$$\delta_A = \delta \sin(\alpha + \beta) \quad , \quad \delta_B = \delta \sin(\alpha - \beta) \tag{15}$$

The deflected angles, θ_x and θ_y, of the bend can be estimated based on the geometrical relationship in the following way;

$$\tan\theta_x = \frac{(\delta_A - \delta_B)\sin\alpha}{2L_1 \sin\alpha - (\delta_A + \delta_B)\cos\alpha} \quad ; \quad \sin\theta_y = \frac{\overline{A'B'}}{2L_1} = \frac{1}{2L_1}\sqrt{(\delta_A - \delta_B)^2 \sin^2\alpha + \{2L_1 \sin\alpha - (\delta_A + \delta_B)\cos\alpha\}^2} \tag{16}$$

where

$$\overline{A'B'} = \sqrt{(\delta_A - \delta_B)^2 \sin^2\alpha + \{2L_1 \sin\alpha - (\delta_A + \delta_B)\cos\alpha\}^2} \quad \text{and,} \quad L_1 = 2\sqrt{\frac{\gamma M_p}{p}} \tag{17}$$

and the parameter γ is introduced to obtain the plastic moment of the bend pipe from that of straight pipe.
In the previous section 2.2.2 one may discuss about four different types of bend deflections which are the inward and outward deflections in the slope and the revetment. These four deflected modes can be evaluated with inserting their corresponding β in Fig.12 as follows.

$\beta = 0$;the slope model (inward bending mode) $\beta = \frac{\pi}{2} - \alpha$; the revetment model(inward bending mode)

$\beta = \pi$; the slope model(outward bending mode) $\beta = \frac{3\pi}{2} - \alpha$; the revetment mode(outward bending mode)

3.2 Case Study

The numerical results of the proposed simplified calculation formula are compared with the shell /beam hybrid FEM analysis. The pipe dimensions and geotechnical parameters to be used herein are shown in Tables 1 and 2.
Fig.13 shows the deflected angle of bend pipe for liquefied ground displacements in the four different cases. The solid line is FEM results, while the line with symbol is the result of the proposed method. Both lines show good correspondence. When one may obtain the relationship between the deflected angle and the ground displacement, the maximum strain of the bend pipe can be estimated from the diagram of Fig.3 which should be furnished as the database for the conversion from the deflected angle to the maximum strain of the bend pipe.

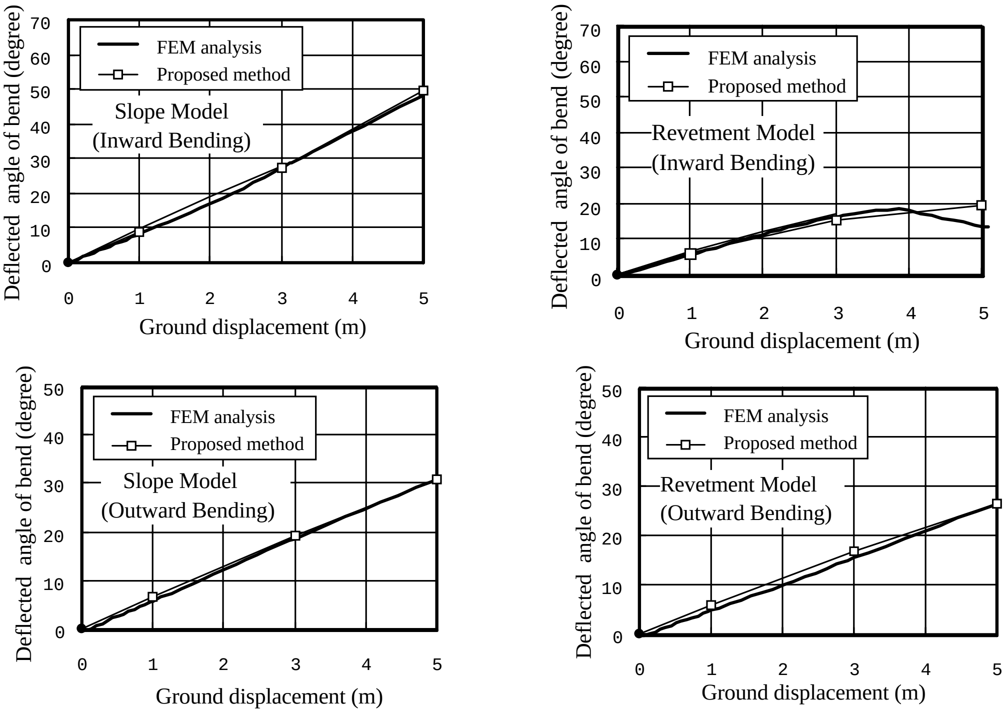


Fig.13 Bending angles of bend portions under lateral spreading.

4. CONCLUSIONS

The simplified design formula to estimate the deflection angle of the pipeline having a bend portion under the lateral spreading in the liquefied ground is developed, in which the plastic limit analysis method is adopted. The result of the simplified formula shows the good coincidence with the FEM analysis.

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