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NUMERICAL STUDY FOR RUPTURE BEHAVIOR OF BURIED GAS PIPELINE SUBJECTED TO SEISMIC FAULT DISPLACEMENT

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SUMMARY

Nonlinear finite element analysis was performed for buried gas pipeline subjected to seismic fault displacement in order to study rupture behavior of the pipeline structure. Pipes of 100mm to 600mm in diameter were studied. According to the calculated results, V- and Z-shaped buckling deformation of the pipeline was observed. The analysis model employed in this paper was found to be very simple and useful for gaining overviews of the rupture behavior of gas pipeline subjected to seismic fault displacement.

INTRODUCTION

Earthquake disaster prevention strategy of our gas company consists of preventive measure, emergency measure, and restoration measure. The preventive measure requires gas pipelines to be designed and constructed on risk assessment, where we assume seismic fault displacement as one of the most disastrous natural influence on pipelines. However, seismic fault influence on pipelines is still under research and not directly applied to current design procedure. In order to obtain knowledge of pipeline behavior in case of seismic fault displacement, we numerically studied rupture behavior of buried gas pipelines across seismic fault. Pipelines studied in this paper were those damaged in Chichi earthquake in Taiwan and those currently used in Osaka area in Japan.

On September 21, 1999, the Chichi earthquake occurred in Taiwan. It was reported that buried gas pipelines underwent bending deformation due to ground displacement at a reverse fault near the Wushi Bridge about 10 km south of Taichung[1]. The bending deformation in a 100A-size pipeline was V-shaped, with the pipeline being bent at three points (Photo 1). The deformation of a 200A-size pipeline was Z-shaped, with the pipeline being bent at two points (Photo 2). There have been virtually no cases of substantial deformation comparable to this case in gas pipelines comprised of welded steel pipes.

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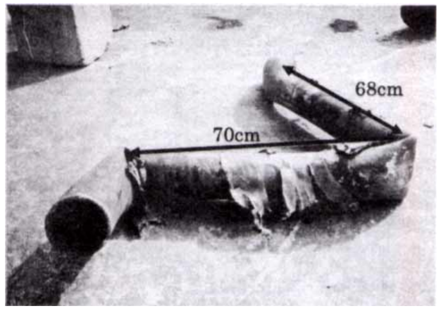


Photo 1 V-shaped deformation in 100A-size gas pipeline

Photo 2 Z-shaped deformation in 200A-size gas pipeline

This report aims to evaluate the safety of buried gas pipelines undergoing fault displacements. Firstly, we conducted a numerical analysis of the bending deformation of gas pipelines that underwent the Chichi earthquake. And then we tried to conduct a numerical analysis of gas pipelines which are used in Osaka for case studies. Furthermore, we examined how much ground displacement a gas pipeline can withstand. The profiles of the pipelines are shown in Table 1 and Table 2.

The tool we used for the analysis was ADINA[2], which is a finite-element analysis program. Material non-linearity and geometrical non-linearity were taken into consideration.

Table 1 Profile of Gas Pipelines Undergoing Bending Deformation in the Chichi Earthquake

Pipeline	Material	D(cm)	t(cm)	D/t	Name in This Report
200A	API X52	21.63	0.90	24	200A-J

Table 2 Profile of Gas Pipelines for case studies

Pipeline	Material	D(cm)	t(cm)	D/t	Name in This Report
150A	SGP	16.52	0.50	33	150A
200A	SGP	21.63	0.58	37	200A
300A	SGP	31.85	0.69	46	300A
400A	SGP	40.64	0.79	51	400A
600A	API X52	60.99	1.20	51	600A-1
600A	API X42	60.99	1.03	59	600A-2
600A	STPY	60.96	0.95	64	600A-3

ANALYSIS METHOD

Finite Element Model

We developed an analysis model as shown in Fig. 1. A fault was assumed to be present within the piping model. A ground displacement was applied to one part of the piping. The other part of the piping was free of the effect of the ground displacement, with the boundary being placed at the fault displacement. Modeling of the pipeline incorporated pipe elements with two nodal points. The pipeline was broken as shown in Fig. 1, into discrete elements of approximate dimension 0.5D in sections near the fault where the pipe would undergo substantial deformation and also approximate dimension 3D in other sections.

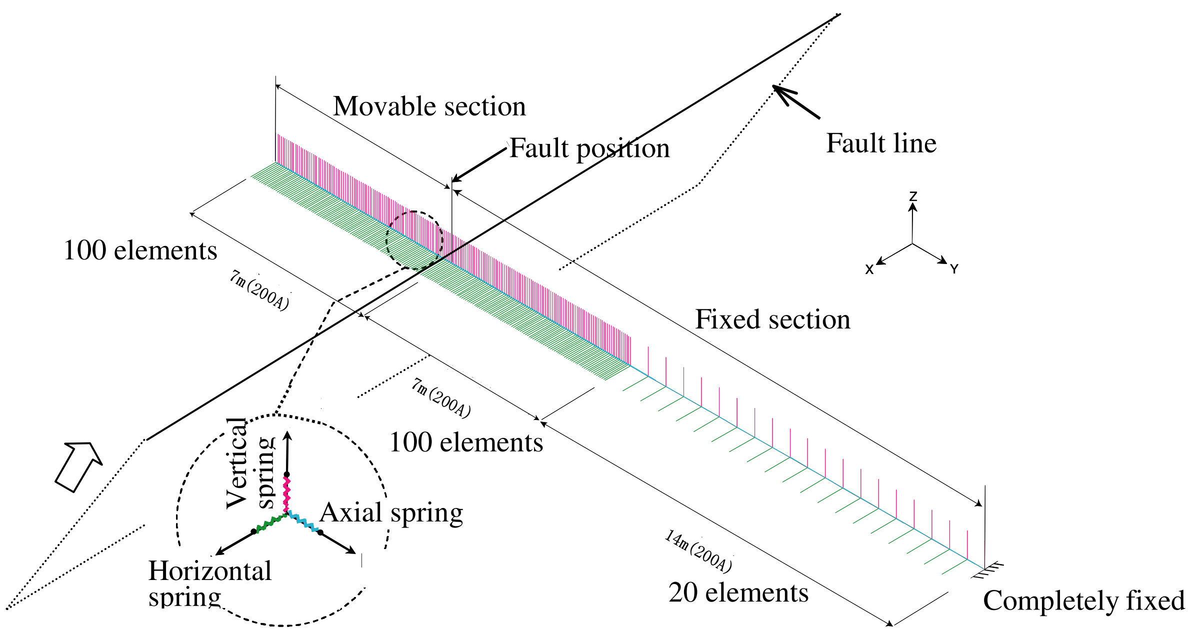


Fig. 1 Analysis Model

Springs representing the ground (ground spring) were applied to each nodal point of the pipe elements in each direction as follows: the horizontal direction perpendicular to the pipe axis (X direction), the axial direction of the pipe (Y direction), and a vertical direction perpendicular to the pipe axis (Z direction). Each ground spring was modeled as a spring element with two nodal points. Regarding the cross-sectional areas of spring elements, the pipe element was multiplied by the pipe diameter to determine values for vertical and horizontal springs. The pipe element length was multiplied by the peripheral length of the pipe to determine the cross-sectional area of the axial spring.

In selecting the lengths for the analysis models, we took into consideration that there were areas of large and small pipe element deformation.

Fault Displacement and Boundary Conditions

In the area undergoing ground displacement, displacements were applied to the nodal points on the ground side of spring elements simultaneously in the pipe's axial direction, the horizontal direction perpendicular to the pipe axis, and the vertical direction perpendicular to the pipe axis, as shown in Fig. 1. The actual amounts of displacement were not precisely known at the fault in the ground where the buried gas pipes shown in Photos 1 and 2 were located. In this report, therefore, the maximum displacements were assumed to be 300 cm in the pipe's axial direction, 200 cm in the horizontal direction perpendicular to the pipe axis, and 80 cm in the vertical direction perpendicular to the pipe axis.

The boundary condition at the end of the pipeline undergoing the ground displacement was the same amount of displacement as the ground displacement. The boundary condition at the end not undergoing the ground displacement was fixation.

Properties of Pipeline Material

The pipeline material was assumed to be elasto-plastic, presenting the bi-linear stress-strain properties as shown in Table 3. We applied the numerical analysis model below, to show degradation in strength at bends in the pipeline and bending deformation. Pipe elements located at bends were deleted when the angles of bend reached the angle achieved at the instant of the maximum bending moment of pipe elements. The relationship between the maximum bending moment and the angle of bend is given in Recommended Practice for Design of Gas Transmission Pipelines in Areas Subject to Liquefaction [3]. We used this relationship for the identification of the angle of bend achieved at the instant of the maximum bending moment. More specifically, the angle of bend (ω) achieved at the instant of the maximum bending moment was determined by testing, and we approximated the relationship between this angle and the ratio of pipe diameter to wall thickness (D/t), using a hyperbolic curve. It is shown in Fig. 2. Then, this hyperbolic curve was used to plot the D/t values of the pipelines for determination of their ω values.

Table 3 Bi-linear Stress-Strain Properties of Pipeline Material

Material Name	Yield Stress σ_y(N/cm^2)	Second Gradient E_T(N/cm^2)	Pipeline Name in This Report
SGP	2.872×10^4	0.00177E	100A ~ 400A
STPY	3.963×10^4	0.00245E	600A-3
API X42	4.093×10^4	0.00252E	600A-2
API X52	4.510×10^4	0.00278E	200A-J , 600A-1

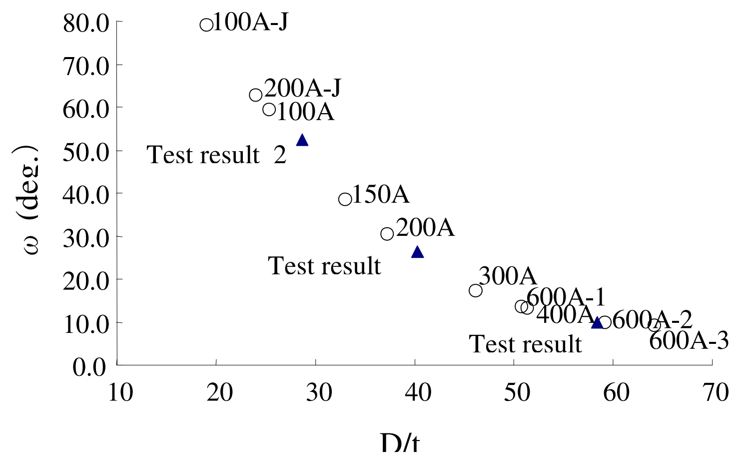


Fig. 2 Angle of bend achieved at the instant of the maximum bending moment (ω), versus ratio of pipe diameter to wall thickness (D/t)

Ground Spring Characteristics

We used the spring characteristics specified in Seismic design guideline of high-pressure gas pipelines [4] and Recommended Practice for Design of Gas Transmission Pipelines in Areas Subject to Liquefaction [3] as ground spring characteristics. Figure 3 through 5 show the spring characteristics. The spring constants specified in Seismic design guideline of high-pressure gas pipelines [4] were applied to the spring in the pipe's axial direction and the spring in the horizontal direction perpendicular to the pipe axis. In the area where the pipeline drives the ground above it in an upwards direction, the spring specified in the Guidelines for Liquefaction and Earthquake-Resistant Designs of High-Pressure Gas Pipelines[3] was used as the spring in the vertical direction perpendicular to the pipe axis. In the area where the ground below the pipeline drives the pipeline up, a linear spring was used, as shown in Fig. 5.

In the area where the pipeline undergoes V- or Z-shaped deformation, it is appropriate to consider that a large relative displacement occurs between the pipe and the ground, resulting in loss of the binding force of the ground. Accordingly, in our modeling, the ground springs attached to the pipe elements in such areas were deleted at the moment the pipe reached an angle of 45 degrees with respect to the horizontal direction.

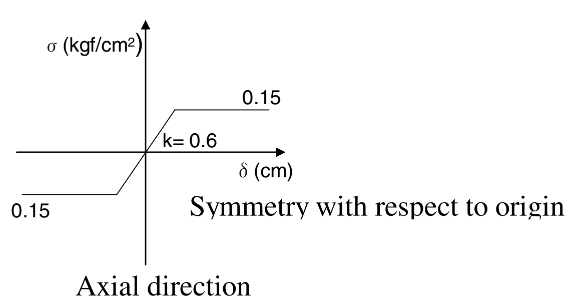
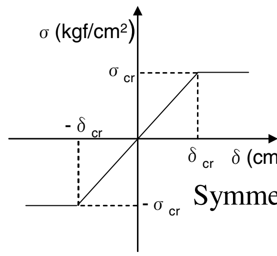


Fig. 3 Ground Spring Characteristics (Axial direction)

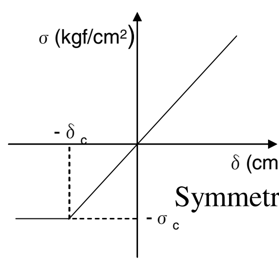


Symmetry with respect to origin

Horizontal direction

Pipeline	σ cr(N/cm^2)	δ cr(cm)
150A	51	2.6
200A	48	2.6
300A	41	2.7
400A	39	2.8
600A	34	2.9

Fig. 4 Ground Spring Characteristics (Horizontal direction)



Symmetry with respect to origin

Vertical direction

Pipeline	σ c(N/cm^2)	δ c(cm)
150A	24	0.9
200A	20	0.9
300A	15	0.9
400A	13	0.9
600A	10	1.0

Fig. 5 Ground Spring Characteristics (Vertical direction)

RESULTS OF ANALUYSIS OF GAS PIPELINES UNDERGOING BENDING DEFORMATION IN THE CHICHI EARTHQUAKE

Figures 6 through 9 show 100A- and 200A-size pipelines undergoing deformation.

The 100A-size pipeline deformed in the following manner: 1) The maximum moment was reached at an axial displacement of 183 cm, the angle of bend being 79 degrees. 2) The bending deformation began to form a V shape at an axial displacement of 240 cm. 3) V-shaped deformation involving three bends was completed at the maximum axial displacement of 300 cm. The lengths between the bends were 105 or 182cm.

The 200A-sized pipeline deformed in the following manner: 1) The maximum moment was reached at an axial displacement of 161 cm, the angle of bend being 63 degrees. 2) The bending deformation began to form a Z shape at an axial displacement of 255 cm. 3) Z-shaped deformation with two bends was completed at the maximum axial displacement of 300 cm. The length between the bends was 250 cm.

The shapes of deformation in pipes obtained through the analysis approximate the actual shapes of deformation shown in Photos 1 and 2.

Thus, the analysis method presented in this report has been proven to be effective for the analysis of bending deformation in buried pipelines undergoing substantial fault displacements.

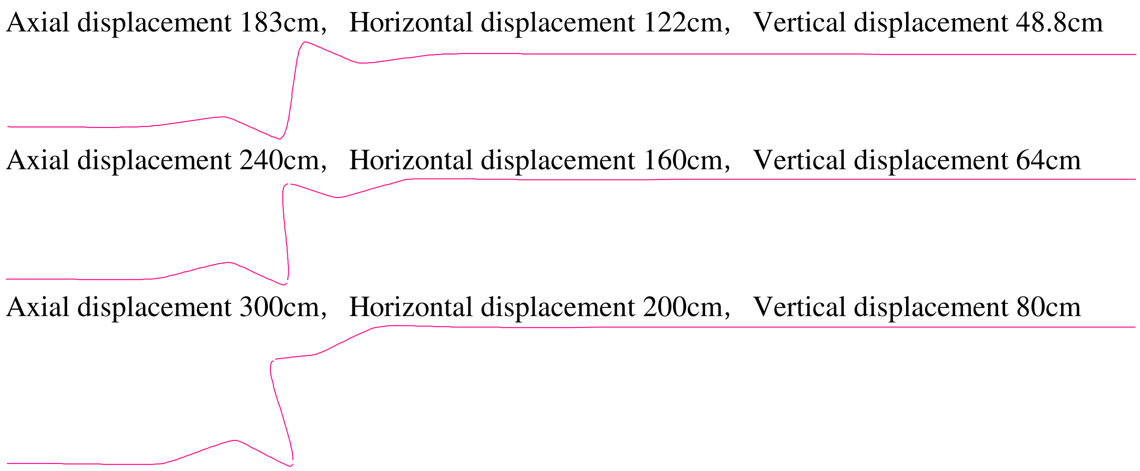


Fig. 6 100A-Size Pipeline Undergoing Deformation (Orthogonal Projection in Horizontal Plane)

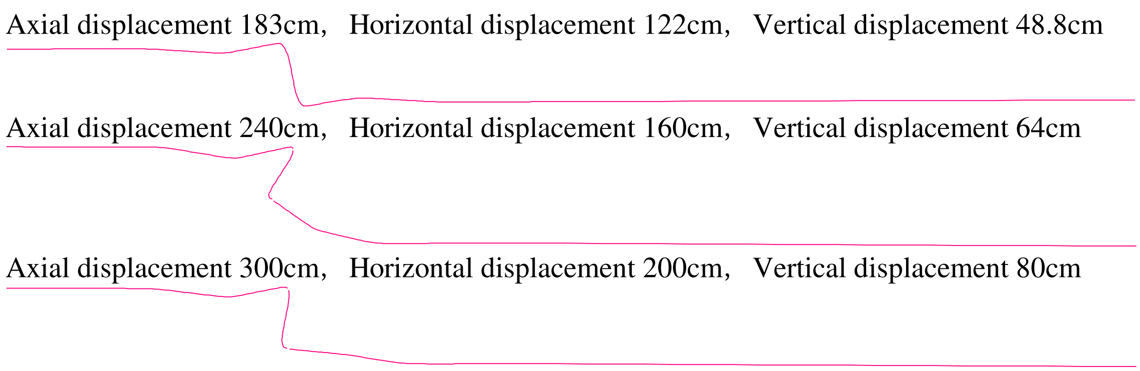


Fig. 7 100A-Size Pipeline Undergoing Deformation (Orthogonal Projection in Vertical Plane)

Axial displacement 161cm, Horizontal displacement 107.3cm, Vertical displacement 42.9cm

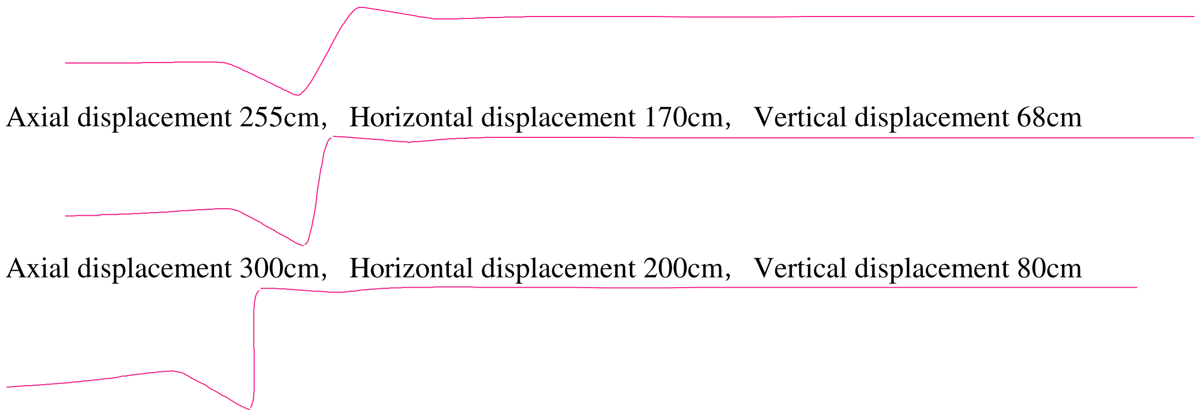


Fig. 8 200A-Size Pipeline Undergoing Deformation (Orthogonal Projection in Horizontal Plane)

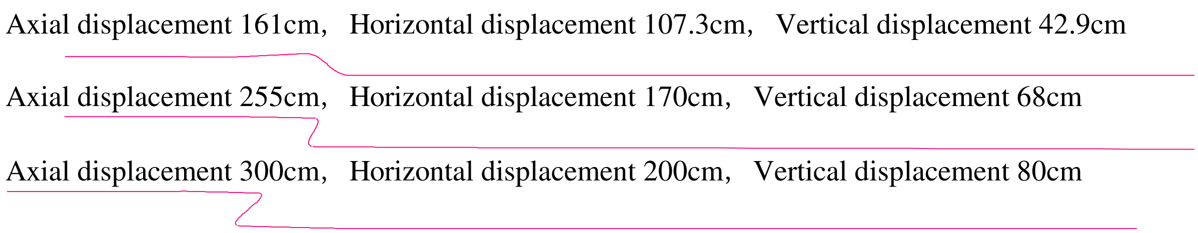


Fig. 9 200A-Size Pipeline Undergoing Deformation (Orthogonal Projection in Vertical Plane)

RESULTS OF CASE STUDIES

We applied the analysis method described in the previous section to various pipelines shown in Table 2 in actual use. Figure 10 shows the final shapes of deformation. These diagrams are drawn as an orthogonal projection of the deformation in a plane containing straight pipeline axes on the right and left of the point of deformation.

The smaller the pipe diameter, the greater the number of bends, the more complicated the deformation, and the shorter the length between the bends. Conversely, the larger the pipe diameter, the fewer the number of bends, the simpler the deformation, and the longer the length between bends.

Figure 11 shows the relationship between bend-to-bend length and the ratio of pipe diameter to wall thickness(D/t). The broken lines in the diagram link materials of the same stress at yield. According to Fig. 11, the larger the ratio of pipe diameter to wall thickness, the longer the bend-to-bend length. Also, it indicates a tendency for the bend-to-bend length to increase with increasing stress at yield.

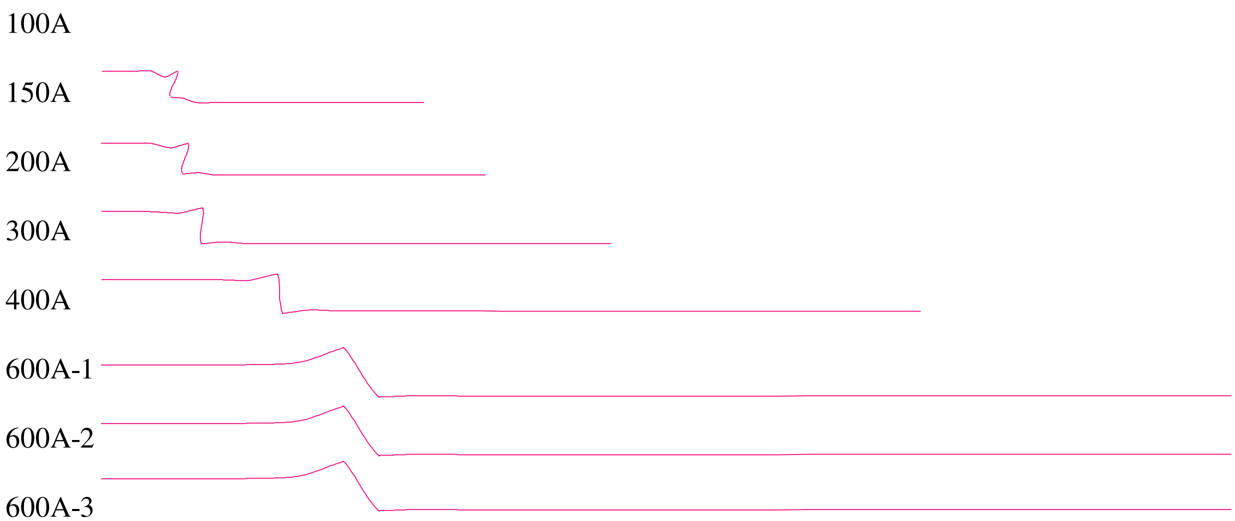


Fig. 10 Final Shapes of Deformation (axial displacement: 300 cm; horizontal displacement: 200 cm; vertical displacement: 80 cm)

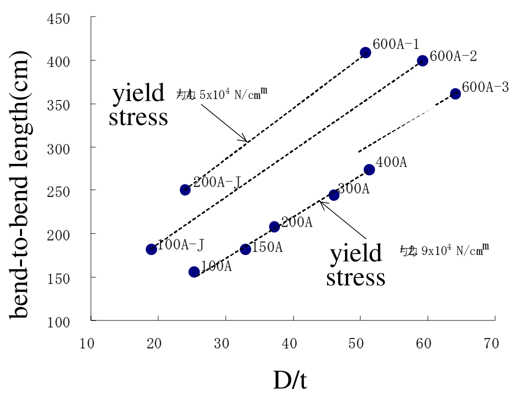


Fig. 11 Relationship between bend-to-bend length and ratio of pipe diameter to wall thickness

SAFETY EVALUATION OF PIPELINES

It is important for our business to ascertain how much ground displacement the pipelines currently in use can withstand in the event of a ground displacement of similar magnitude to that discussed in this report.

Fault displacement at the instant of maximum moment

Figure 12 shows the relationship between fault displacement and ratio of pipe diameter to wall thickness. This relationship is seen when a bend in the pipeline reaches the angle of bend achieved at the instant of maximum bending moment.

As shown in Fig. 12, there is a hyperbolic relationship between fault displacement and ratio of pipe diameter to wall thickness at the instant of maximum bending moment. In other words, the smaller the ratio of pipe diameter to wall thickness, the larger the fault displacement, and vice versa.

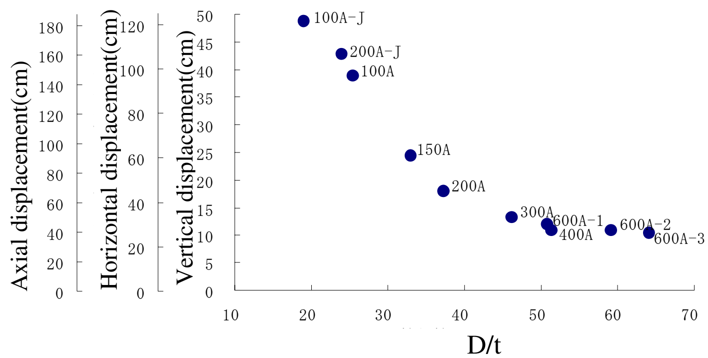


Fig. 12 Relationship between Fault Displacement and D/t at the Instant of Max Bending Moment

Fault displacement at the instant of critical angle of bend

Figure 13 shows the relationship between fault displacement observed when a bend in the pipeline reaches the critical angle of bend (hereinafter referred to as the "critical fault displacement"), and the ratio of pipe diameter to wall thickness. The critical angle of pipeline bend was calculated by the equation (1) proposed in the Seismic design guidelines of high-pressure gas pipelines[4]

There is an approximately linear relationship between the fault displacement observed when a bend in the pipeline reaches the critical angle of bend, and the ratio of pipe diameter to wall thickness, as shown in Fig. 13. In other words, fault displacement increases with increasing ratio of pipe diameter to wall thickness.

$$\omega_{sc} = \left\{ \frac{44t_s}{100D} \left(8k - \frac{2k^2}{3} \right) + \frac{3.44}{\sqrt{2} \cdot \sqrt{D/t_s}} \left(1 + \frac{\varepsilon_f}{2} \right) \right\} \cdot \frac{180}{\pi} \qquad (1)$$

where,
ω_{SC}: critical angle of bend of straight pipe (deg.)
D: outside diameter of straight pipe (cm)
t_S: nominal wall thickness of straight pipe (cm)
L_S: reference length for determination of axial compression deformation and angle of bend of straight pipe (= 64・D)
ε_f: 0.35
k: ratio of $L_S/2$ to outside diameter D (= 3.2)

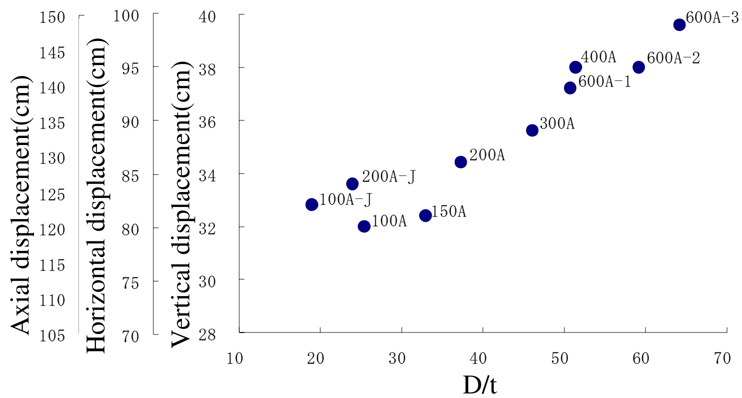


Fig. 13 Relationship between Fault Displacement at the Instant of Critical Angle of Bend and Ratio of Pipe Diameter to Wall Thickness

CONCLUSIONS

1. We have developed an analysis method used to express bending deformation subjected to fault in pipelines for numerical calculation.
2. This method is effective for reproducing the bending deformation in 100A- and 200A-size pipelines observed in the Chichi earthquake.
3. We have ascertained how much ground displacement a pipeline can withstand, through calculation of the ground displacement occurring at the instant of a pipeline's critical displacement.

It is necessary to make further study of ground spring characteristics, amounts of fault displacements and their directions, and deletion methods for pipe elements in bends and ground springs presented in this report.

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