13th World Conference on Earthquake Engineering
Vancouver, B.C., Canada
August 1-6, 2004
Paper No. 3114

# SEISMIC PERFORMANCE OF WATER SUPPLY STEEL PIPELINES UNDER LARGE GROUND DEFORMATIONS

**Takeshi KOIKE[1],Yoshikazu NAKAJIMA[2], Nobuhiro HASEGAWA[2], Kazuaki KIRIYAMA[2], Hiroshi GOHYAKUDA[2], Shusuke FUJITA[2], Takahiro YABUGUCHI[2], Shunsuke SHIOZAKI[2], Masayuki SOTOYAMA[2]**

## SUMMARY

The purpose of this study is to assess the seismic performance of steel fabricated pipe elbows called Miter Bend which are widely used for water pipelines.
Based on the experimental and numerical studies, a simplified practical design formula was also developed so as to estimate the maximum seismic deflections of bend pipes under possibly large permanent ground displacement. Finally, a new seismic design method of Miter bend was proposed for a water pipeline installed in the liquefied ground.

## INTRODUCTION

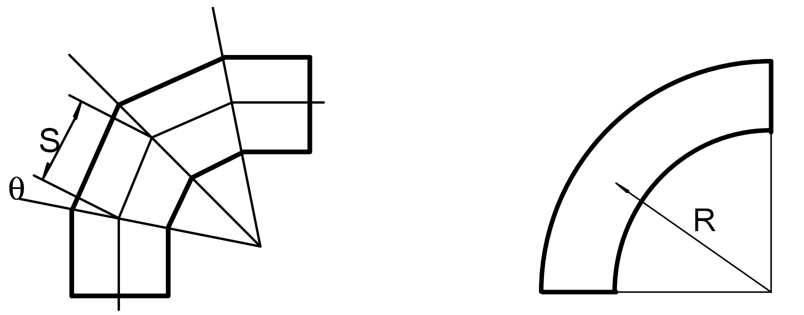
Seismic damages of various kinds of water supply pipelines are often observed not only at the pipe joints but also at the geometrical pipe elements, while there are not yet established methods how to design those pipeline elements suffering from the severe strong ground motions (JSCE[1],JRA[2]) or large scale permanent ground displacements. When a pipeline is forced by a lateral spreading due to a liquefaction or a fault movement, plastic collapse or buckling onset must be taken into consideration in order to establish a new seismic design method for the water supply steel pipeline including pipe bends and tee-junctions.

This report includes the full-scale experiments of miter bend, the ultimate strength of which is investigated in the in-plane and out-plane bending modes, while numerical calculations using a FEM shell model were conducted in order to compare both experimental and numerical results. Finally, a simplified design formula was proposed for the bend portions.

Miter bend which is fabricated with segmented pipe elements shown in Figure 1(1) is widely used for water pipelines (WSP[3]). It must be noted that smooth bends used for gas pipelines are different from the miter bend, in which the pipe wall of the miter bend is thin and spatially homogeneous, while the pipe wall of smooth bend, on the other hand, shows comparatively large thickness and spatially inclination. Current studies on the ultimate performance of bend deflection were devoted to the gas pipelines, while

[1]Professor, Musashi Institute of Technology, Tokyo, JAPAN. E-mail: tkoike@sc.musashi-tech.ac.jp
and also ex-member of Japan Water Steel Pipe Association
[2]Members of Japan Water Steel Pipe Association

those studies for the water pipelines are very limited. Recently Japan Gas Association (JGA[4]) developed a practical formula to estimate the bend deflection for large permanent displacements. The purpose of this study is to assess the applicability of the practical formula which was especially developed for smooth bends of gas pipelines to the miter bend.




(1)Miter bend (2)Smooth bend

**Figure 1 Various bends**

## FULL-SCALE EXPERIMENT OF STEEL WATER PIPE BENDS

### Methods of experiments

The full-scale miter bends of 400A and 600 mm OD in Figure 2 were used for the bending tests (WSP[5,6]), in which the applied forces were given in the closing and opening modes to the end points of the bend. Table 1 shows the dimensions of the test specimens, where 90 degree miter bends were adopted. The measuring items were the displacement between the end points, applied loads, bending angle and strain distributions over the bend surface. Progressive behaviors of buckling were also observed at each loading step.
The internal pressure was not applied except for the use of leak check in which slightly low air pressure was given.

**Table 1 Dimensions of structural components**

| ITEM | BEND | PIPE |
|---|---|---|
| Specification | JIS-G-3451 | JIS-G-3443 |
| Bend angle | 90 bend | Straight pipe |
| Dimensions | 400Ax6t | 400Ax6t |
| Actual dim. | 406.4mmx6.14mm | 406.4mmx6.14mm |
| Dimensions | 600Ax6t | 600Ax6t |
| Actual dim. | 609.6mmx6mm | 609.6mmx6mm |

### Pipe deflections

The test results can be expressed by the relationships between the bending moment and deflection angle. Figure 3 shows the inward bending mode, while Figure 4 is for the outward bending mode. The numerical results due to FEM analysis are also shown on these figures.
In the inward bending mode, the progressive deflections are concentrated at the central cross section, while, in the outward bending mode, the initial deflection takes place at the central cross section, but the following deflection makes the stiffness softening together with a local buckling at the most compressive

zone of the miter bend, then the critical buckling initiates after the peak bending moment. The two bending modes makes different behaviors in the curves of the moment and deflection angle.

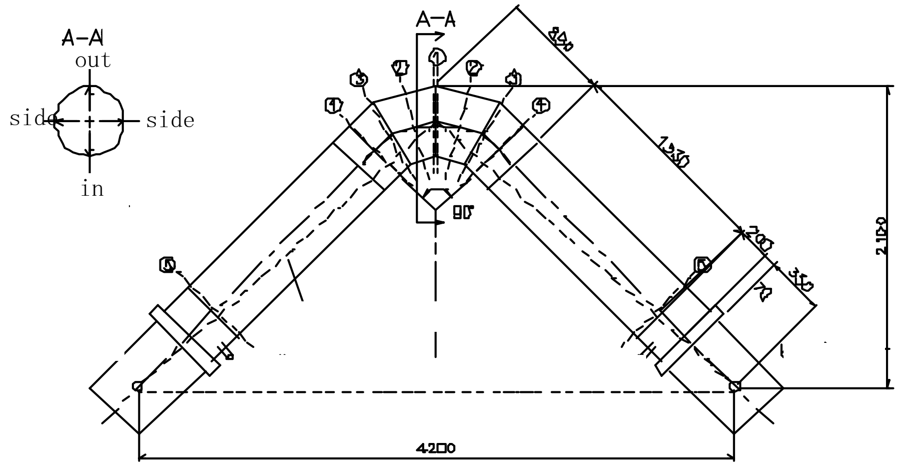



**Figure 2 Experiment of the miter bend**

In the inward bending mode in Figure 3, the peak moment is located at about 5 degree which means that the buckling initiates after 5 degree. Due to the mechanical limit of the test machine, the maximum deflection angle is about 55 degree. In the outward bending mode in Figure 4, the initial stiffness changes at 5 degree , then the peak moment is located around 15 degree, and the maximum deflection angle is about 22 degree which corresponds to the angle at the buckling failure.

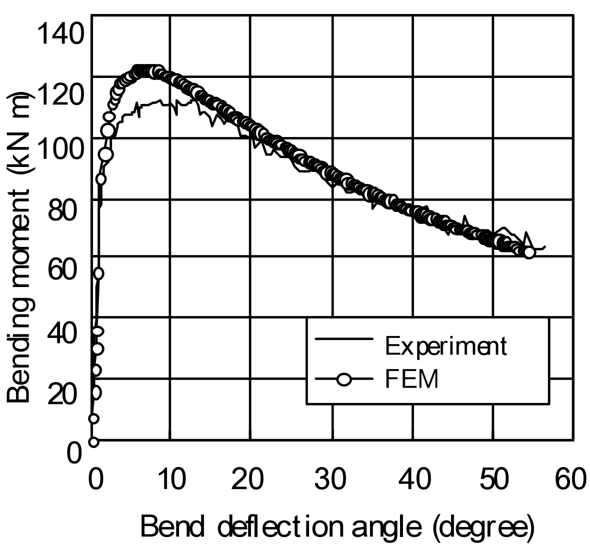



**Figure 3 Moment and deflection angle relationship of miter bend in the inward bending mode**

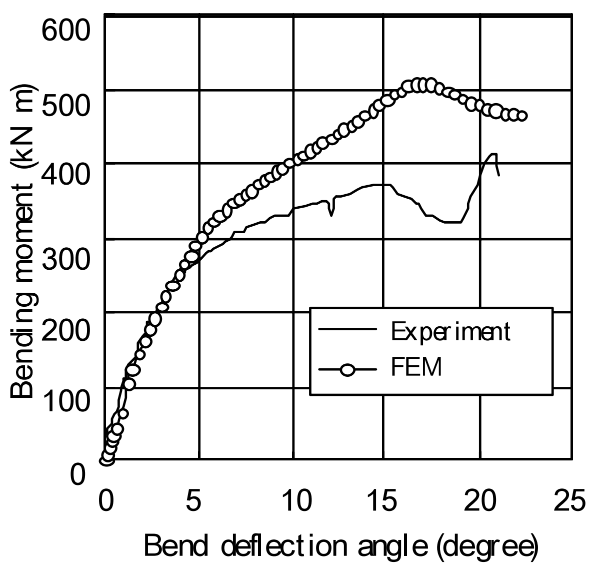



**Fig.4 Moment and deflection angle relationship of miter bend in the outward bending mode**

**Table 2 Conditions of FEM analysis**

| ITEM | | DESCRIPTION |
|---|---|---|
| (1)FEM code | | MARC k-7.2 |
| (2)FEM element | | 4 nodes shell element |
| (3)Pipe dimensions | Diameter<br>Thickness<br>Curvature<br>Bend angle | 609.6 mm<br>6.0 mm<br>1.225 x Diameter<br>90 degree |
| (4)Material characteristics | Yield stress<br>Hardening coeff. | 350 N/mm$^2$<br>3 N/mm$^2$ |

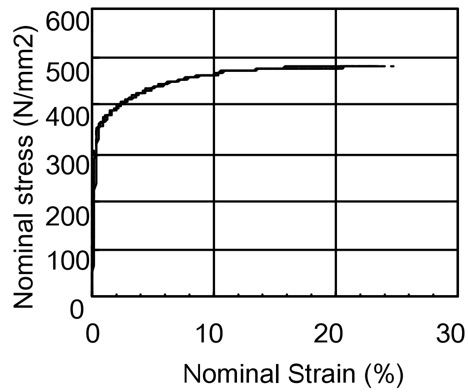



Figure 5 Normal stress and strain Relationship of pipe specimen

**Numerical simulations**

The nonlinear finite element analysis code of MARC was used to simulate the experimental results of the miter bend deflections. The stress-strain curve in Figure 5 was used for FEM analysis which was taken from the tensile test of the specimen of the full-scale pipe element.
Table 2 shows the conditions of FEM analysis for 600A miter bend.

## THE MAXIMUM MOMENT OF MITER BENDS

The segmented bend, so-called Miter Bend as shown in Figure 1, is widely used in the water supply pipelines. The structural properties, flexibility factor *n* and stress intensification factor *i*, can be expressed with the pipe factor *h* in the following way (Koike[7],Koike and Imai [8]).

$$h = \frac{Rt}{r^2} \quad , \quad n = \frac{1.52}{h^{5/6}} \quad , \quad i = \frac{1.8}{h^{2/3}} \tag{1}$$

in which the radius *R* of curvature of the bend is given with the length *S* shown in Figure 1(1) by

$$R = \frac{S \cot \theta}{2} \tag{2}$$

Once the flexibility characteristics of the miter bend is known, the stress and deflection of the bend can be easily expressed in the following way.

$$\sigma_B = i\frac{M}{Z} \qquad\qquad \frac{\Delta\psi}{\psi} = n\frac{MR}{EI} \tag{3}$$

in which *Z* and *EI* are section modulus and bending rigidity of the Miter bend.
As shown in the full-scale experiments of Figures 3 and 4, the maximum bending moments are different for the inward and outward bending modes, so that the following two equations are furnished:

$$M^i_{\max} = C_i M^i_{cr} \quad , \quad M^o_{\max} = C_o M^o_{cr} \tag{4}$$

in which $C_i$ and $C_o$ are determined by the experimental results, and the fully plastic moment $M_p$, its corresponding plastic deflection angle $\theta_p$ and plastic strain $\varepsilon_p$ are given by

$$M_p = \frac{4}{3}\sigma_y\left[\left(\frac{D}{2}\right)^3 - \left\{\frac{(D-2t)}{2}\right\}^3\right] \quad , \quad \theta_p = \frac{\pi}{2} n \frac{M_p R}{EI} \quad \text{and} \quad \varepsilon_p = i\frac{M_p}{EI}\frac{D}{2} \tag{5}$$

The maximum moment of the bend must be determined from both of the experimental and the theoretical results. The difference between both results can be obtained from the peak value of the normalized bending moment $M/M_{cr}$ as shown in Figure 6, which can provide

$$C_i = 1.1 \qquad \begin{array}{lll} C_o = 1.0 & \text{for} & D/t \le 66 \\ C_o = 0.5 \sim 1.0 & \text{for} & 66 < D/t < 100 \\ C_o = 0.5 & \text{for} & D/t \ge 100 \end{array} \tag{6}$$

where

$$M_{cr}^{i} = 0.8h^{0.6}M_p \quad , \quad M_{cr}^{o} = M_p \tag{7}$$

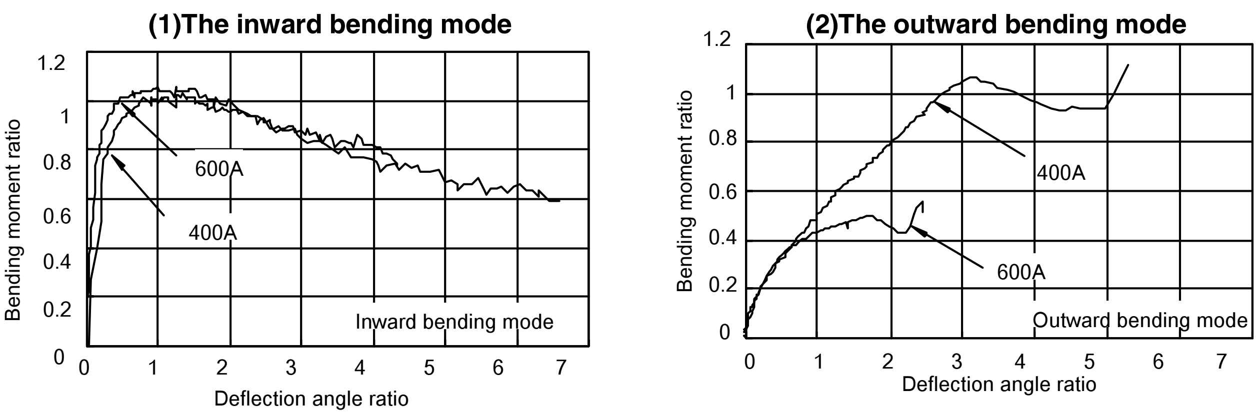



**Figure 6 Normalized bending moments $M/M_{cr}$ for the deflection angles $\theta/\theta_p$**

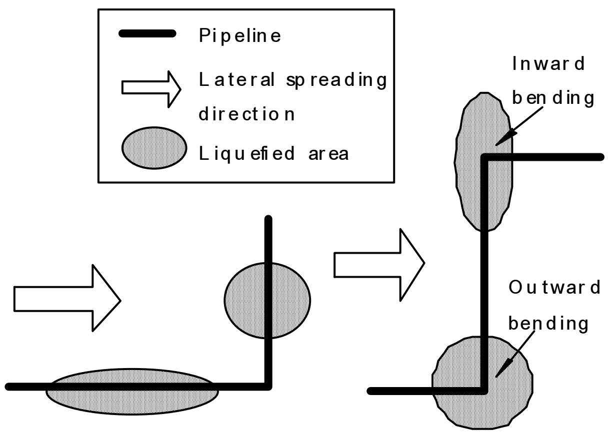
## PIPE DEFORMATIONS FOR PERMANENT GROUND DISPLACEMENTS

### Simplified formula

When a straight pipeline passes through the liquefied zone, the ground movement in the axial direction of the pipeline may produce a slippage to the pipeline, while the ground movement perpendicular to the pipe axis may introduce a large bending deflection as shown in Figure 7. If a bend pipe is located in the liquefied area, the ground movement produces two types of bending behaviors; inward bending mode and outward bending mode. When a pipeline is forced by several meters of a large ground displacement due to a liquefaction, the buried pipeline is deformed in-elastically together with the surrounding ground. Non-linear FEM analysis was applied for a beam model of buried bend in order to predict the in-elastic deflection behavior of buried bend under a large ground displacement.

For instance, Hamada et al [11] suggest that the maximum ground displacements due to a liquefaction may not exceed about 3 meters in Japan. Figures 8 and 9 show the deformed profile when the pipeline to be located along the shore line is suffered by a liquefaction-induced ground displacement of 3 meters. Figure 9 suggests that a large ground displacement may create plastic bends at a bend corner and at a pipe portion apart from that bend. Figure 9 shows that the stress concentration is accumulated not only at the bend, but also at the straight pipe portions. Since the water supply pipe has a thin-wall thickness, therefore the plastic bending is easy to take place.

A simplified model can be introduced herein as shown in Figure 10 in order to obtain a simplified design formula to estimate the bend deflection for an excessive large ground displacement. The three plastic hinge model (JGA[4]) was proposed in JGA where a new seismic design method(Takada[9]) was developed in order to calculate the maximum deflection of the bend for an excessive large ground displacement due to a liquefied ground spreading. The same approach is adopted in this study.




**(1)Straight pipe segments (2)Bend pipe portions**

**Figure 7 Pipeline segments under liquefaction hazard**

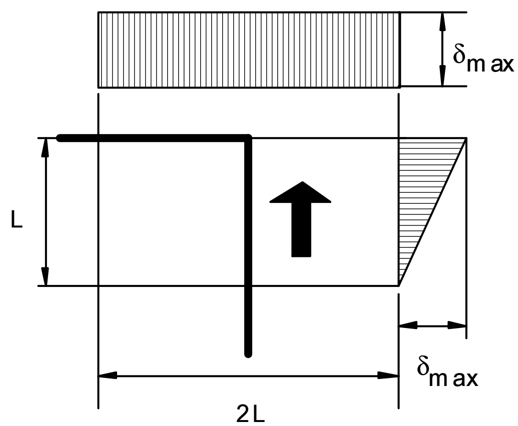



**Figure 8 Analytical model of bend pipe configuration and lateral spreading due to liquefaction**

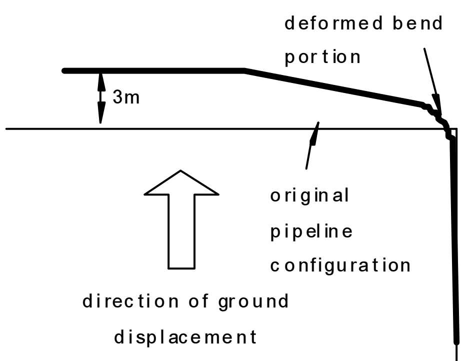



**Figure 9 Numerical simulation of a bent corner and its connected pipes in the outward bending mode**

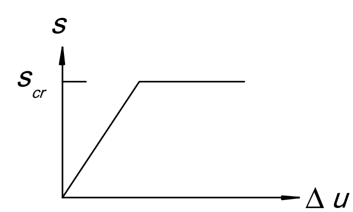



**Figure 10 Shear stress-strain relationship of the soil in the liquefied ground**

From the geometrical relationship, the following formula can be obtained for the bending angle of a miter bend.

$$\theta_c = \left|2\theta_y - 2\alpha\right| \tag{8}$$

in which

$$\sin(\theta_y) = \frac{\overline{A'B'}}{2L_1} = \frac{1}{2L_1}\sqrt{(\delta_A - \delta_B)^2 + \sin^2\alpha + \{2L_1\sin\alpha - (\delta_A + \delta_B)\cos\alpha\}^2} \tag{9}$$

and

$$\delta_A = \delta \sin(\alpha + \beta) \quad , \quad \delta_B = \delta \sin(\alpha - \beta)$$

$$L_1 = \sqrt{\frac{2(M_{\max s} + M_{\max b})}{p}} \quad , \quad p = DS_{cr} \tag{10}$$

in which $p$ is the soil reaction stress defined with $S_{cr}$ in Fig.10, and

$\theta_c$ :deflection angle of the bend(radian)
$\delta$ :horizontal displacement(m)
$\alpha$ :a half of the original bend angle(radian)
$L_1$ :interval between two hinges(m)
$\beta$ :direction of the PGD(radian)
Inward mode: $\beta = -\alpha$

Outward mode: $\beta = \frac{3}{2}\pi - \alpha$

$M_{maxs}$:the maximum bending moment of pipe(kNm)

$$M_{\max s} = M_p$$

$M_{maxb}$:the maximum bending moment of bend(kNm)

$$M_{\max b} = M^i_{\max} \quad or \quad M^o_{\max}$$

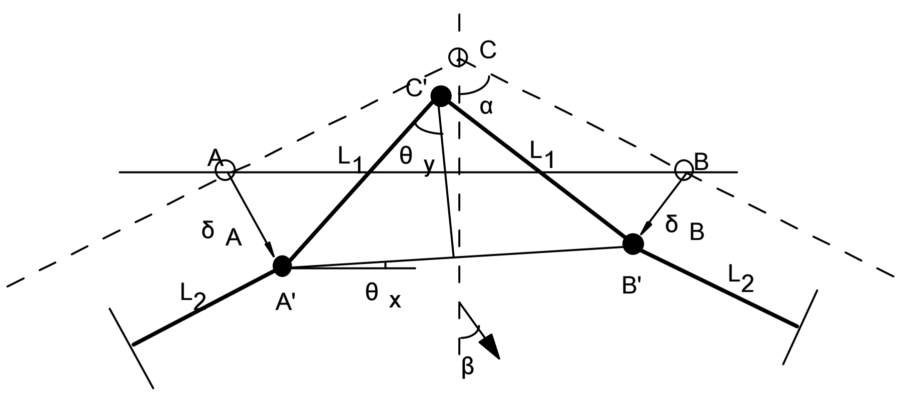
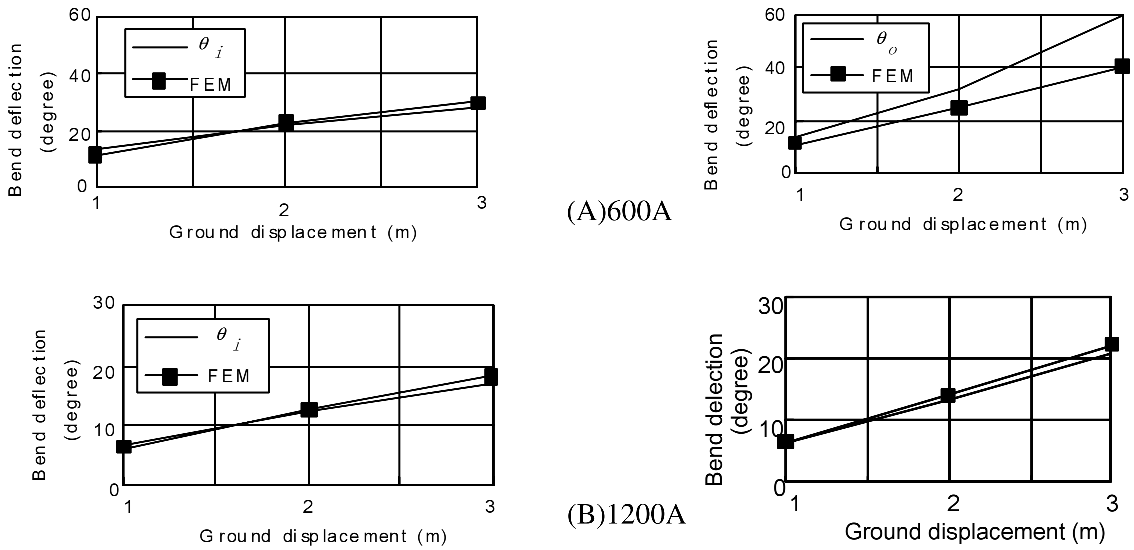



**Figure 11 Deformed pipeline due to an excessive ground displacement**

## Comparison with FEM results

Figure 12 shows the comparison between the results by the simplified formula and FEM calculations for the inward and outward bending modes of 600A and 1200A bend pipes. Except from the outward bending mode of 600A, all the other modes express the good coincidence for several permanent displacements of 1m,2m and 3m.




**(1)The inward bending mode** **(2)The outward bending mode**

**Figure 12 Comparisons for the calculation result by the proposed method and that of FEM analyses**

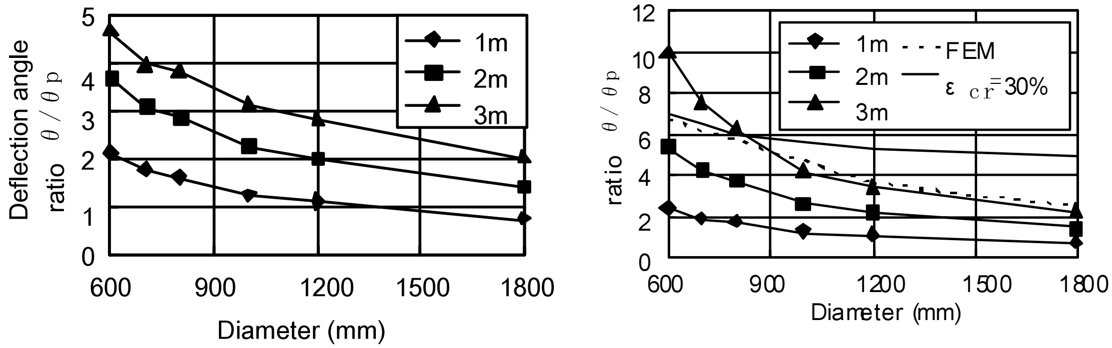
**Seismic performance of bend deflection**

Figure 13 shows bend deflections for various diameters of Miter bends, in which the ordinate of the figure is normalized with the plastic bending angle to be defined in Eq.(5). This figure describes that large diameter pipe has large bending rigidity enough to create a long distance of $L_1$ in Eq.(9) which decreases the deflection angle forced by the ground displacement. The bending deflection of the outward mode in Figure 13(2) expresses comparatively larger deflection than that of the inward mode, which suggests that more attention should be paid for the bend alignment in the outward bending mode against the lateral spreading in a liquefied ground.

The numerical results by FEM for 3m ground displacement are also added in Figure 13(2) which shows, however, some discrepancy in a smaller diameter than 900A.
In order to obtain the seismic performance of Miter bend, the following formula was developed as shown in Eq.(11) in which the parameter *Cp* was introduced to take into consideration of the non-linear behavior of bend deflection in the plastic region. The value of *Cp* can be estimated to be 0.5 from Figure 14.

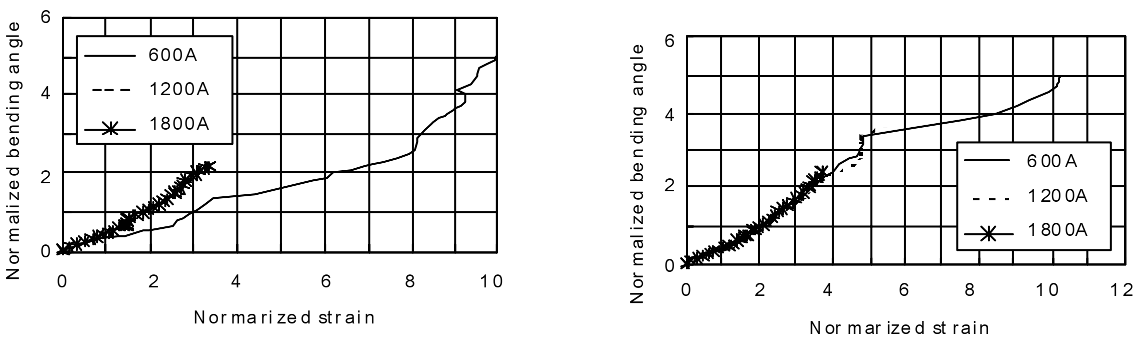
$$\frac{\theta_{cr}}{\theta_p} = C_p \frac{\varepsilon_{cr}}{\varepsilon_p} \quad , \quad C_p = 0.5 \tag{11}$$

in which $\theta_{cr}$ means the ultimate bending angle of Miter bend when the maximum bending strain $\varepsilon_{cr}$ was assumed to be 30%, the value of which was used as the critical value for smooth bends of high-pressure gas pipelines in the seismic design against the liquefaction hazard. This ultimate bending angle is also shown with the solid line ($\varepsilon_{cr}$ =30%) in Figure 13(2), which suggests that major bends used for water pipelines may be safe for a possible large ground displacement of 3 m, if the critical strain value can be assumed to be at least 30%.




**(1)The inward bending mode** **(2)The outward bending mode**

**Figure 13 Deflection angle ratios for various diameters of bends**




**(1)The inward bending mode** **(2)The outward bending mode**

**Figure 14 Relationship between the equivalent strain and bending deflection angle for various Miter bends**

## CONCLUSIONS

The seismic capability of the buried bend pipes under ground shaking and ground movement were studied through the experimental and numerical research works. In-plane inward and outward bending tests of the full-scale miter bends were investigated to obtain the deflection performance in the ultimate limit state of the miter bend.

The results were summarized as follows:

(1)In the inward bending mode, the progressive deflections are concentrated at the central cross section, while in the outward bending mode, the initial deflection takes place at the central cross section, but the following deflection makes the stiffness softening together with a local buckling at the most compressive zone of the miter bend, then the critical buckling initiates after the peak bending moment.

(2) FEM analysis can simulate the deflection behavior of the bend in the inward bending mode, while the analytical result makes an underestimate of the experimental result in the outward bending mode after the yielding level. This underestimate was caused by the difficulty in the post buckling simulation of the miter bend in the outward bending mode.

(3) Simplified design formulas were furnished to estimate the deflection angle for the permanent ground displacement.

(4)Based on the design formula developed herein, experimental results express good performances not only in the ground shaking, but also in the ground displacement.
(5)Major bends used for water pipelines may be safe for a possible large ground displacement of 3 m, if the critical strain value can be assumed to be at least 30%.


## ACKNOWLEDGEMENT

This study was conducted during fiscal 1998 to 2002 by Japan Water Steel Pipe Association. We would like to express our gratitude to all related parties belonging to this association for their financial supports.


## REFERENCES


1.Japan Society of Civil Engineers "Proposals on Seismic design guidelines by JSCE." JSCE,1996.
2.Japan Road Association " Design guideline of roads, Japan Road Association." 1996.
3.Japan Water Works Association " Seismic design code for water facilities." JWWA,1997.
4.Japan Gas Association " Recommended practice for earthquake resistant design of gas pipeline." 2000.
5.Japan Water Steel Pipe Association " Seismic design standard for buried water steel pipeline." edited by WSP, 1997.
6.Japan Water Steel Pipe Association " Compression test of water steel pipe." edited by WSP, 1996.
7.Koike, T. " Estimation of buried pipe strains under seismic risk." Journal of JSCE, JSCE, Vol.331, pp.13-24, 1983.
8.Koike, T and Imai T. "Structural displacement analysis of buried pipelines against strong earthquake ground motions." Journal of Structural Engineering, JSCE, Vol.44A, pp.1647-1658, 1998.
9.Takada, S. et al "Analysis for non-linear behavior of buried pipeline due to liquefaction with lateral spreading." Journal of Structural Engineering, JSCE, Vol.46A, pp.947-1956, 2000.
10.Koike, T. et al "Large deformation behaviors of miter bend used for water pipelines." Journal of Structural Engineering, JSCE, Vol.46A,pp.851-858, 2000.
11.Hamada, M. and Wakamatsu K. "Study on horizontal ground displacements due to liquefaction." Journal of JSCE, JSCE, Vol.596/III-43, pp.189-208, 1998.