SEISMIC PERFORMANCE OF COMPLICATED PIPELINE NETWORK

Y. Kuwata[1], S. Takada[2] and S. Yamasaki[3]

[1] *Associate Professor, Dept. of Civil Engineering, Kobe University, Kobe, Japan*
[2] *Emeritus Professor, Dept. of Civil Engineering, Kobe University, Kobe, Japan*
[2] *Graduate Student, Dept. of Civil Engineering, Kobe University, Kobe, Japan*
Email: kuwata@kobe-u.ac.jp

ABSTRACT :

Since the pipeline network is composed of deformed pipes such as bend, Tee, and several fitting as well as straight pipes, its seismic performance is complicated. The concentrated stress due to the seismic load generally acts on the deformed pipes so that the relative displacement between soil and pipe occurs. From the practical sense, the earthquake response analysis of straight pipeline is not enough to explain the seismic performance of whole pipeline network. This study developed a new numerical analysis method, which can simulate the seismic behavior of complicated pipeline network with several branches. Moreover, seismic performance of the pipelines network jointed by bend and Tee pipes is analyzed with comparison of the straight pipelines in terms of the displacements of jointed parts quantitatively. Finally the evaluation method to assess the seismic performance of the complicated pipeline network is discussed throughout the analysis.

KEYWORDS: seismic performance, pipeline, complicated network, deformed pipe,

1. INTRODUCTION

Seismic response of underground pipelines has been studied by several analysis models of pipelines against the seismic loads such as wave propagation, liquefaction-induced lateral spreading and faults offsetting displacement. However most of them focus on the model of straight pipelines with/without joints or on the relation with different seismic loads. The pipeline network is a highly complicated system composed by deformed pipes such as bend, Tee, and several fitting as well as straight pipes. The stress due to the seismic load generally is focused on the deformed pipes so that the relative displacement between soil and pipe occur. From the practical sense, the earthquake response analysis of straight pipeline is not enough to explain the seismic performance of whole pipeline network. The seismic performance of complicated pipeline with deformed pipes shall be made clear by the analysis techniques. For the seismic design guideline of continuous pipeline, the conversion factor for bend and Tee pipe, which expresses the factor of pipe strain to the ground strain according to pipe diameter or thickness, is proposed by Koike and Imai (1998). Though it focuses on the continuous pipeline, it would be useful when such kind of simplified conversion factor for the jointed pipeline is obtained by the numerical analysis.

This study developed a new numerical analysis method, which can simulate the complicated pipeline behavior with several branches arranged by three dimensions considering complicated tensile/compression and bending characteristics at the jointed parts, and nonlinear soil stiffness and pipe material. This study focuses on the seismic responses of the pipelines network composed of bend pipes and tee joints, with comparison of the straight pipelines in terms of displacements of jointed parts quantitatively. Finally the evaluation for the seismic performance of the complicated pipeline network is discussed.

2. ANALYTICAL MODEL

The seismic behavior of underground pipeline subjected to wave propagation is calculated by the proposed model as shown in Figure 2.1. The pipeline is composed of segmented beam elements which have structural

non-linear characteristics of axial tension/ compression and bending. The joint is expressed by the couple of springs, having axial force-displacement relationship and moment-rotation angle relationship. These springs take into account the non-linearity, but their response is calculated independently. Moreover, the pipeline model with several joints is supported by the axial and transverse soil springs, expressing the slippage at the soil and pipe interface. The end of the beam can be assign into several conditions such as fixed, pin, or free. Since the pipeline model can layout in three dimensions, this study is easy to treats behavior of the bend and Tee pipes. However these pipes are modeled as several straight beam elements and the de-centering of bend pipe stiffness is not taken into account herein.
In the calculation of pipeline under the seismic wave propagation, the finite element formulation is solved by the increment of load. Besides of ground displacement of wave propagation, concentrated force, distributed force, thermal load can be applied to this analysis. This calculation procedure is proposed by Takada et al. (1988).
There was the pipe failure beneath the river embankment during the earthquake in Noto, Japan in 2007. This damage was caused by the lateral displacement and settlement of the embankment. Using this modeling and calculation, the actual pipe damage was simulated well and its result shows the verification of the applicability of the present numerical method (Kuwata and Takada, 2007).

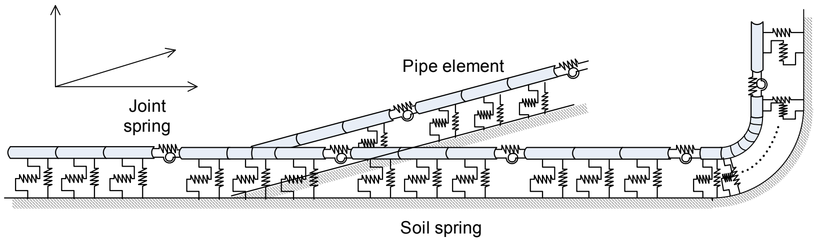
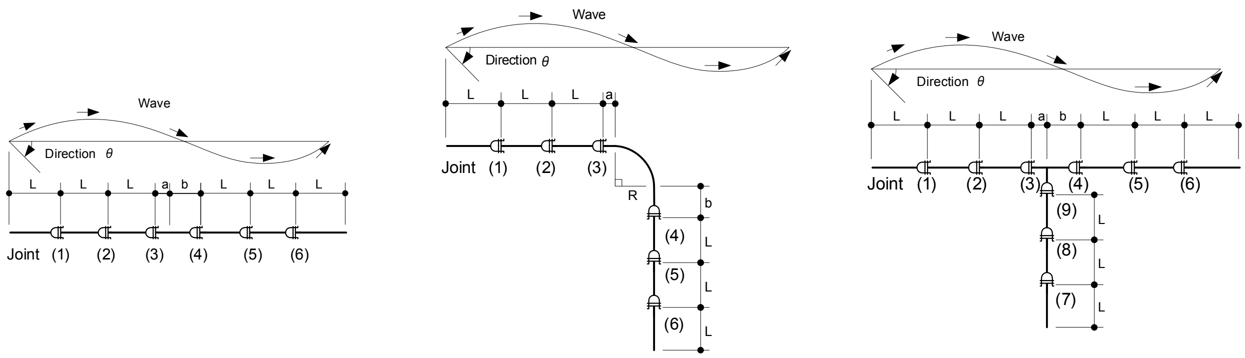


Figure 2.1 Analytical model of pipe element and various springs

3. SEISMIC PERFORMANCE OF SEGMENT PIPE
3.1 Modeling
In order to make clear the seismic performance of deformed pipe by the numerical analysis, the segment pipe models composing deformed pipe are set as shown in Figure 3.1. The target pipe is the ductile cast iron pipe (DIP) with K-type joint used in Japan. The model of straight pipeline is used for the comparison with the others. Besides of the deformed pipe, the three straight pipes are connected to the deformed pipe and the boundary condition of pipeline is assumed to be free to avoid the local concentration of stress. The pipe properties ranging from diameter 100, 200 to 300 mm are referred to the specification of pipe in Japan as listed in Table 3.1. The shape of bend and Tee pipes do not have symmetry from the center of pipe. The straight part of pipe is modeled by 1m length of pipe elements, whereas the bending and branch part is divided by a few centimeters. Those allowable expansion displacements are determined by the specification as to be 4, 5, 5 mm (corresponding 1% of pipe length) for the diameter 100, 200 and 300mm of pipe respectively, whereas the allowable bending angles are as to 4, 4 and 3 degrees. Their joint mechanical systems for tension/compression



(a) Straight pipes (b) Bend pipes (c) Tee pipes
Figure 3.1 Analysis model of segment pipe

Table 3.1 Pipe property

Diameter (mm)	100	200	300
Length *L* (mm)	4,000	5,000	5,000
Length *a* (mm)	42	43	47
Length *b* (mm)	150	200	250
Outside diameter (mm)	117	220	323
Thickness *t*/*t*'(mm)*	8/9	8/11	8/13
Young modulus (kN/mm^2)	1,600,000		
Tensile stiffness (kN/mm^2)	420		

Note*) *t*: thickness of straight pipe, *t*': thickness of bend pipe

Table 3.2 Soil spring property

K_{g1}(kN/cm^2)	2.6
K_{g2}(kN/cm^2)	5.1
Wavelength (m)	153.9
Wave speed (m/s)	150
Yield displacement (mm)	26

Note) Vs: shear wave velocity, K_{g1}: Soil spring stiffness in the pipe axial direction, K_{g2}: Soil spring stiffness in the pipe transverse direction,

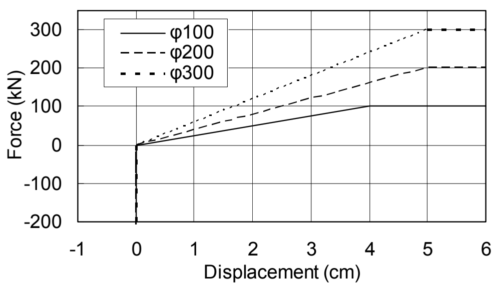


Figure 3.2 Tensile/compression joint property

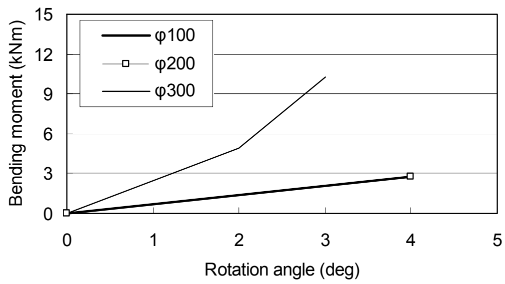


Figure 3.3 Bending joint property

and rotation are referred to the results of test as shown in Figures 3.2 and 3.3, and their non-linearity is considered in the calculation.

The soil spring is modeled according to the seismic design guideline of Japan Water Works Association (JWWA, 1997) for three types of soil stiffness as listed in Table 3.2. Moreover, proposed soil spring enables to simulate the non-linear behavior such as slippage between the pipe and surrounding soil by adopting the characteristics of the perfect elastoplasticity. The characteristics of soil spring assumed to a little soft in order to cause larger ground strain in this study. Above parameter about pipe and soil spring are set deterministically.

3.2 Response rate

The numerical calculation of pipeline model was done in many cases for a set of model with random variables of the wave phase and the direction of wave propagation to the pipe axis. In such kind of calculation, we can consider uncertainty in the several parameters (Elhmadi and O'rouke, 1990). Beside of wave phase and wave direction, the parameters are set deterministically. The result is discussed in the point of maximum response of deformed joints in terms of displacement and angle at the joints to the allowable values, expressed by,

$$A_{\max\_j} = Max\left(\frac{R}{T}\right)_p \times 100 \tag{3.3}$$

Where, $A_{\max}$: response rate for the deformed joint (%), *R*: response displacement of joint in (mm) or (degree), *T*: allowable value of joint, *j*: type of joint, *p*: type of response (displacement or angle)

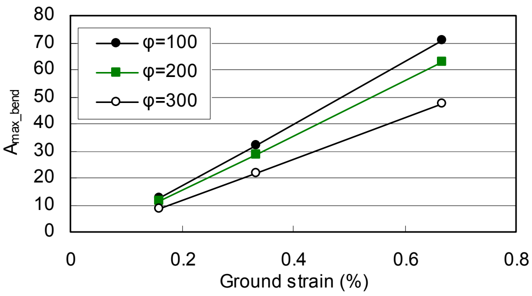


Figure 3.4 Response rate of bend pipe

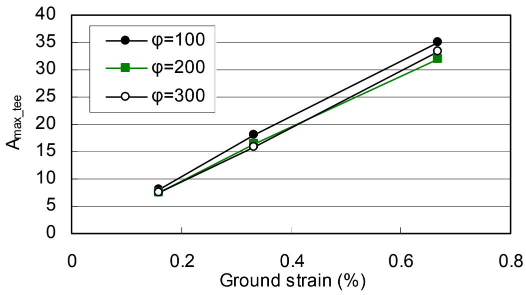


Figure 3.5 response rate of Tee pipe

When the surface ground velocity is input as 24, 50, 100 cm/s, the response rate of the jointed pipe are obtained as shown in Figures 3.4 and 3.5. Seismic design of water pipeline in Japan guides the two levels of design input by the deterministic approach. 24 cm/s of seismic velocity corresponds to Level 1 ground motion, which occurs one or two times for service period of structure, and 100 cm/s corresponds to the upper bound of Level 2 ground motion, which rarely occurs, but if so, severe damage provokes to the structure.
The maximum value of the joint for each ground velocity is the one obtained from 500 cases of calculation with random values of load parameter. At the ground strain 0.67%, some of pipes start to slip between soil and pipe. However less than it, there is no slippage observed. Therefore the response ratio of the deformed pipe increases linearly as the ground strain does as well. As the general response tendency, the joint axial displacement of straight pipe is more predominant than the rotation angle. Therefore the response rate of the straight pipeline is determined by the allowable displacement of joint. Whereas, in the case of bend and Tee pipe, the displacement occurs as the rotation angle rather than axial displacement. This study focuses on the maximum value at the joint displacement. Thorough out the analysis, the responses in 500 cases look to follows the exponential distribution. Therefore the maximum value is completely far from the mean of distribution. The small diameter pipe with 100mm in diameter shows a little bit higher response than the others.

3.3 Response factor to straight pipeline

The seismic responses of deformed joint pipes are compared with that of straight pipe. The response factor of deformed pipe is defined as the response rate of deformed pipe divided by that of straight pipe as expressed by,

$$F_j = A_{\max\_j} / A_{\max\_straight} \tag{3.2}$$

Where, F_j : response factor of deformed pipe *j*.

The response factor of deformed pipe is summarized as Figures 3.6 and 3.7. For the response factor of Tee joint, the diameters 200 and 300mm shows to be 1.0, equal to the response of straight pipe. Only the diameter 100mm has 1.5 times of straight pipe response. On the other hand, the bend pipe has different factors by the diameter. In case of diameter 100mm, 3 times of the straight pipe's response shows in maximum, even the diameter 300mm indicates 1.5 times. These values are constant to the ground strain. Response rates of straight pipe and deformed pipe mode due to different mode. Since the joint displacement is predominant either in axial extension or in rotation, it is thought that the response factor does not change.

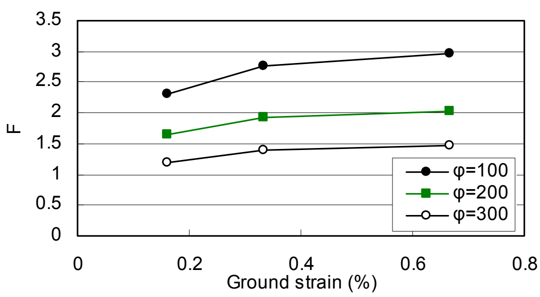


Figure 3.6 Response factor of bend pipe

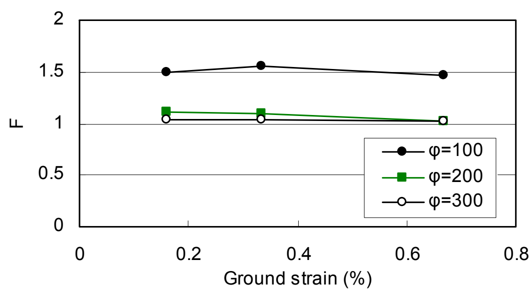


Figure 3.7 Response factor of Tee pipe

4. SEISMIC PERFORMANCE OF PIPELINE NETWORK

Seismic response of a part of pipeline network would not always the same as that of segment pipes. The pipeline network involving bend and Tee pipes in the different directions is modeled as Figure 4.1. All the boundary conditions are assumed to be free. Twelve bend pipes and ten Tee pipes are examined in the same calculation. Only the pipeline with 100mm diameter is studied for one example. The pipe property and soil spring property is the same used in Section 3. Calculation is done in 500 cases as well. Comparisons under the velocity 24 and 100 cm/s are discussed.

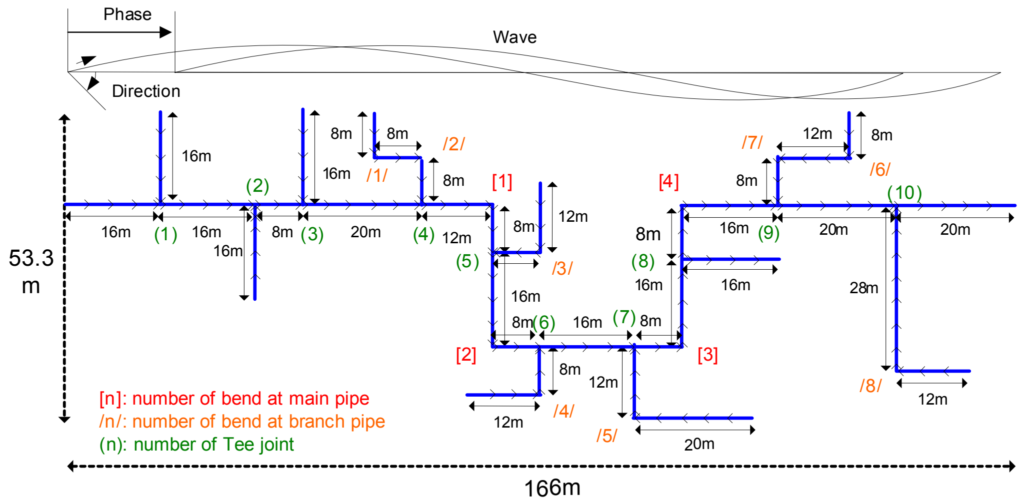


Figure 4.1 Pipeline network model

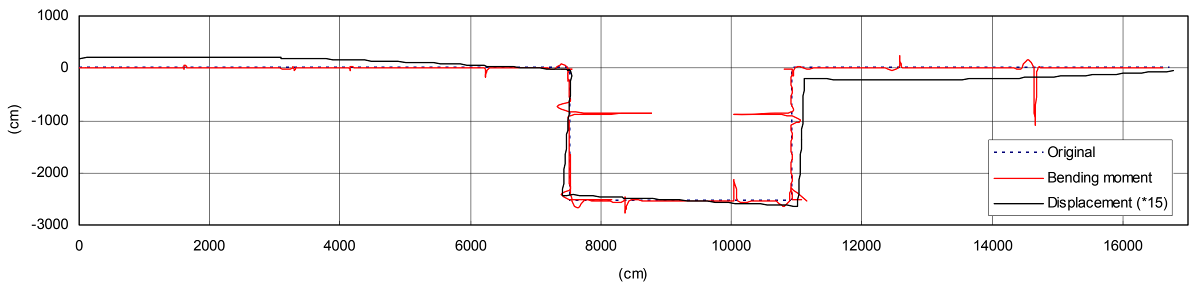
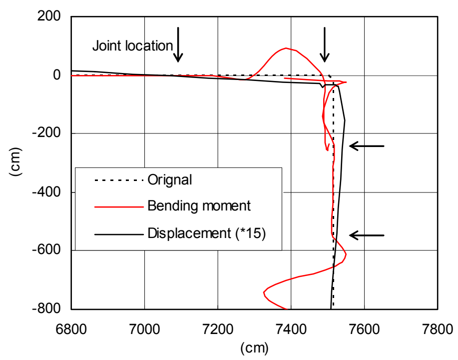


Figure 4.2 Seismic response of main pipe (in case that main bend pipe [1] has the largest rotation angle, 100cm/s)



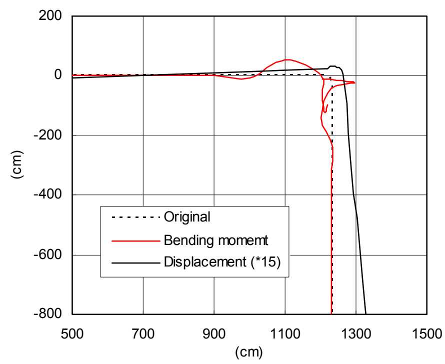


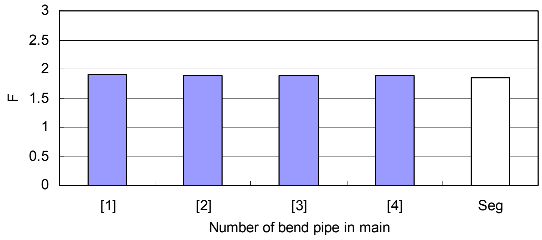
Figure 4.3 Seismic response near main bend pipe [1] (same case as Figure 4.2)

Figure 4.4 Seismic response of bend pipe in the segment model

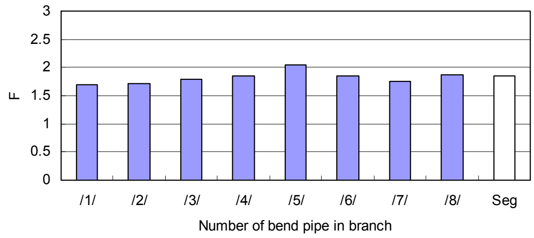
Here, the calculation is checked with an example of the result. Figure 4.2 shows the pipe displacement and bending moment distributions of main pipe when the maximum response rate of bend pipe [1] is obtained among the calculation trials. This response rate of main bend [1] is 4.49, which is 1.5times larger than the response rate of the segment pipe model. As it can be seen in Figure 4.2 and Figure 4.3 that is in close-up near the main bend pipe[1], the bending moment near the bend and Tee pipes does not distributed widely. The nearest joint absorbs the moment by the rotation angle. However, the branch pipe from Tee pipe (5) restrains the displacement and the large bending moment acts on near the main Tee pipe [5]. The joint at short elbow side of the bend pipe [1] is caused large deformation.

Figure 4.4 shows the seismic response of the bend pipe in the segment model when the largest response rate is obtained. In this segment model, the neighbor pipes near the bend pipe are restrained. Therefore the response

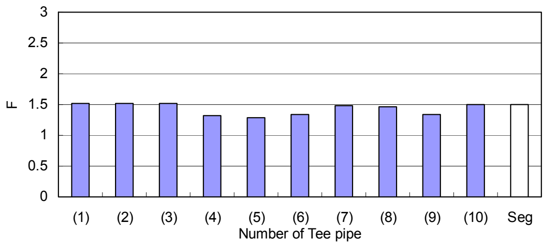
does not reach the values in the network model. These effects can be mentioned by only this network model.
In terms of the response factor in the network, the seismic performance of deformed pipe is examined as shown in Figures 4.5 and 4.6. In case of 24 cm/s in velocity, the response factors of bend and Tee pipes in the network are the same as those in the segment pipes. Minor differences are due to random variable in the trials of calculation. This result indicates that the seismic response of deformed pipe is larger than that of straight pipe under the seismic environment of Level 1 ground motion; 1.8 times for the Tee pipe and 1.5 times for the bend pipe.
However, when the ground motion increases up to 100cm/s, the response factor in the network also becomes high and does not meet with that of the segment pipe. The seismic response in the networks is affected by the restraint due to the neighbor joint behavior as mentioned above. Not only the failure mode of joint changes to the others, but somewhat response of joint restrains its neighbor response. The case obtaining the maximum response rate is very specific among the trails of calculation and this response rate is greatly dependent the network model studied. In this network the response factor is at most 1.5 time of that in the segment pipe. Between the network layout and ground motion level, the reasonable response factors should be introduced.



(a) Bend pipe in main

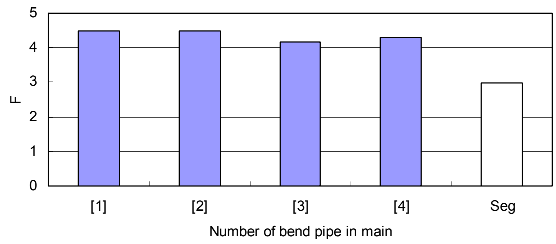


(b) Bend pipe in branch

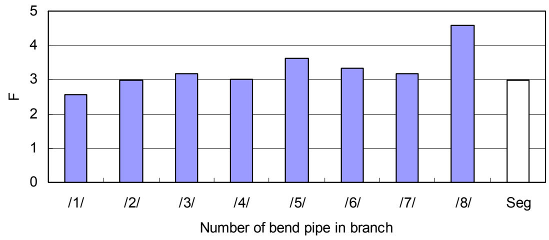


(c) Tee pipe

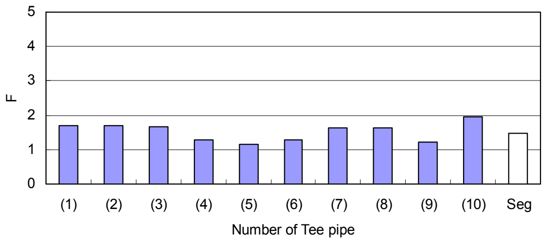
Figure 4.5 Comparison of response factor between segment and network pipelines (V=24 cm/s) (In figures, "Seg." means the response factor in case of segment pipe study)



(a) Bend pipe in main



(b) Bend pipe in branch



(c) Tee pipe

Figure 4.6 Comparison of response factor between segment and network pipelines (V=100 cm/s) (In figures, "Seg." means the response factor in case of segment pipe study)

5. CONCLUSIONS

This study analyzed the seismic response of complicated pipeline networks and shows the performance of the deformed pipe quantitatively. Followings can be summarized as conclusions.

- Under the Level 1 ground motion, the seismic response of deformed pipe in the pipeline network is almost same as that of segmented pipe and it is larger than that of straight pipe.

- The response factor to the straight pipe response becomes 1.8 times for the Tee pipe and 1.5 times for the bend pipe under the Level 1 ground motion.
- In the network model, the response of deformed pipe is restrained by the neighbor pipe behavior and becomes larger than that in the segment model.
- The largest response factor is obtained specifically among the trials of calculation under the layout of the network model in the case of 100cm/s. The effects to the response factor should be considered more with the network model and ground motion level.

REFERENCES

Elhmadi, K., O'rouke, M. J. (1990). Seismic damage to segmented buried pipelines, *Earthquake Engineering and Structural Dynamics*, **19**, 529-539.

Japan Water Works Association. (1997). *Seismic Construction Guideline and Explanation for Water Works*, Tokyo, 71-76 (in Japanese).

Japan Ductile Iron Pipe Association. (2005). *Handbook*, 256-269 (in Japanese).

Koike, T., Imai, T. (1998). Structural displacement analysis of buried pipelines against strong earthquake ground motions, *Journal of Structural Engineering, JSCE, A*, **44:3**, 1647-1658 (in Japanese)

Kuwata, Y., Takada, S. (2007). An analysis on damage to main water facilities during the Noto Hanto earthquake, *Memoirs of Construction Engineering Research Institute*, **49**, 163-172 (in Japanese).

Takada, S., Horinouchi, N., Tsubakimoto, T., Tsuchiya, M., Ogawa, Y. (1988). Earthquake resistance evaluation of service junctions in a small-diameter steel pipeline, *Proceedings of Ninth World Conference on Earthquake Engineering*, Japan, **VII**, 85-90.