TRANSVERSE LOADING ON FAULT CROSSING SEGMENTED BURIED DUCTILE IRON PIPELINES SUBJECTED TO DIP FAULTINGS

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As different soil resistance against pipe relative movement in upward and downward directions for normal burial depths of pipe, soil load size on pipe in two sides of dip fault is different. This study investigates the applicability of introduced simple method to estimate the transverse load on fault crossing buried pipelines in vertical plane for FEM analysis. In this way, results of FEM analyses are verified by experiments on a segmented ductile iron pipe with 93mm diameter and 15m length installed at a 60cm depth from the ground surface in the moderate dense sand backfill condition. Fault movement, totally 35cm, had three same steps occurring in reverse way and intersection angle of 60 degrees with the pipe.

Key words: Soil-Pipeline Interaction, Reverse Fault, Experimental Test, FEM Analysis, Segmented Buried Pipeline, Ductile Iron Pipe

1. INTRODUCTION

As human life undeniable dependence on pipeline systems, access to these facilities even through high seismic risk areas, is inevitable. One of these seismic risks which has caused significant damages on pipeline systems in previous seismic events is movement of faults crossed by them.
Uninterrupted serviceability and uninterrupted performance of pipeline systems which have important role in post-earthquake recovery of human society needs comprehensive knowledge about these structures and consequently, appropriate methods for their analysis and design.
Studies on structural behavior of fault crossing continuous buried pipelines, especially those cross strike slip faults, have considerable progress and recently have led to some reasonable analytical equations which are confirmed by comprehensive numerical models, experimental tests or comparison with previous real seismic events [1][2][3].
Yet, existing uncertainties in performance of mechanical joints of segmented pipelines in addition to complicate behavior of pipes subjected to dip faulting, because of different resistance of soil against relative movement of pipe in upward and downward directions has kept the researches on this problem at early stages.
Herein, we tried to do verified numerical evaluation of transverse load applied on a segmented buried pipeline in vertical plane due to reverse faulting with considering different behavior of soil in two sides of subsidence trace and study on the pipe behavior as well.
In this way, we tried to find an appropriate reduction factor to reduce soil bearing resistance for use as its upward stiffness in computer-aided analyses. This method has been used by Takada et al. for PVC pipes [4] and soil basic stiffness in their research was based on recommendations of Manual for seismic design of gas distribution pipelines published by Japan Gas Association [5].
As verification, with the unique chance for experimental tests in Kubota Corporation, Japan, we were able to compare results of FEM analyses with experimental tests.

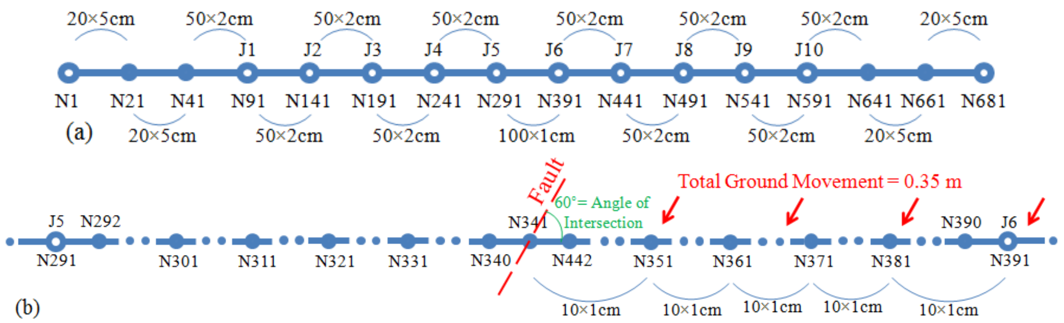


Figure 1. Geometry of FE model for entire buried pipeline (a), Geometry of FE model for pipe-fault intersection point vicinity (b)

2. MODEL DESCRIPTION

In this study, a segmented ductile iron pipeline, nominally Φ75, with external diameter of 93mm and 7.5mm wall thickness in total length of 15m composed by nine 1m length segments between two 3m length ones, at both ends, is considered. Pipeline is buried at the depth of 60cm in the moderate sandy soil with density of γ=17.7kN/m^3, sub-grade reaction of k=40800kN/m^3 and subjected to a reverse faulting.

Modeling details of this problem in both computer aided simulation and experimental tests are as follows.

2.1. FEM modeling

Using recently developed progressive methods for pipeline modeling such as Discrete Element Method (DEM) or procedures using shell or combined shell-beam elements as pipe bar have undeniable advantages[6][7][8]. Though, such methods are useful for fully detailed observation of pipe internal attempts in critical status like during or after buckling and performance of joints through failure or post failure stages.

As mentioned previously, in this study, we are concentrated on reasonably accurate numerical evaluation of soil transverse load on buried pipeline at the both sides of dip faults. Hence, for analysis of models, we used FEM software, namely DYNA2E, which basically was developed for analysis of framed structures but can be used in this regard by introducing pipe as beam elements connected to springs as surrounding soil.

2.1.1 Modeling of Pipe

Fig.1 shows the geometry adopted for the proposed finite element model. A 15m long straight pipeline was considered for the analysis. The fault was assumed to cross the pipeline at the center of its length. The pipeline was modeled by using linear beam elements. The entire 15m length of the model was divided into five regions. Element size was kept uniform within each region. Region 3, including the fault crossing point had a total length of 1m (0.5m on either side of the fault crossing point). The smallest element size of 1cm was adopted in this region, since according to Seismic Guidelines for Water Pipelines published by American Lifelines Alliance[9] and in order to get adequately accurate and converged results, length of elements is decided less than one-tenth of pipe diameter in vicinity of intersection point of pipe and fault. The element size was increased to 2cm in regions 2 and 4, which began at the ends of region 3 on both sides and extended up to 5m. Regions 1 and 5 represented the rest of the length of the model on both sides and they had elements of size of 5cm (half of the pipe diameter).

2.1.2. Modeling of soil-pipe interaction

As shown in fig.2, the soil surrounding the pipeline is modeled by pairs of springs having axial stiffness only, with one end attached to the pipe body and the other end fixed. The first spring is perpendicular to the pipe and represents the transverse interaction between pipe and soil; the other is tangential to the pipe and represents the sliding interaction of pipe with surrounding soil. Input displacements are specified at the fixed ends to simulate fault displacements. Both kinds of springs are active in both directions of relative displacement between pipe and soil. The direction of all soil springs is modified at each step of solution procedure to preserve the angle they made with the pipe in the initial configuration.

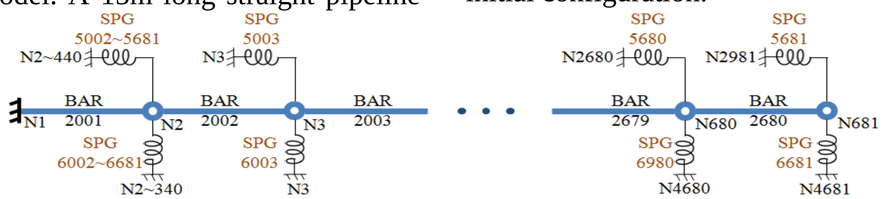


Figure 2. Soil equivalent springs in FE mod

Figures 3 and 4 shows the properties of soil equivalent springs used in finite element analysis modeled in this study.

Stiffness of tangential springs is estimated according to guideline of Japan Ductile Iron Association (JDPA) [10] as follows:

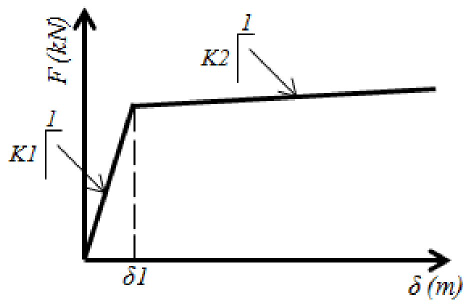
$$\mathrm{K}_{\mathrm{axial}} = \mu \times \pi \times \mathrm{D} \times \gamma \times \mathrm{H} \times \mathrm{L} / \delta_1 \qquad (1)$$

Where, "K_{axial}" is axial stiffness of soil equivalent spring (kN/m), "μ" is soil-pipe surface interaction coefficient, "D" is external diameter of pipe (m), "γ" is soil density (kN/m^3), "H" is pipe burial depth from ground surface to Center of pipe (m), "L" is pipe element length (m) and "δ_1" is achieved by experiment and equals to 0.002 (m).

In terms of transverse spring stiffness, it is based on simple concept of equality of soil stiffness to subgrade reaction times to interfaced area of soil and pipe projection in horizontal plane, so we have:

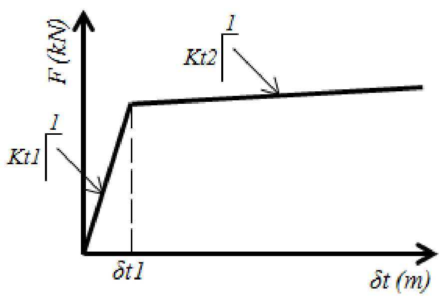
$$\mathrm{K}_{\mathrm{transversal}} = K \times \mathrm{D} \times L \qquad (2)$$

Where, "$K_{transverse}$" is transverse stiffness of soil equivalent spring (kN/m), "K" is subgrade reaction (kN/m^3), "D" is external diameter of pipe (m) and "L" is pipe element length (m).



Stiffness	Foot Wall Side	Hanging Wall Side
K1	334.3 kN/m	334.3 kN/m
K2	0.3343 kN/m	0.3343 kN/m
δ1	0.002 m	0.002 m

Figure 3. Stiffness diagram for soil frictional drag springs

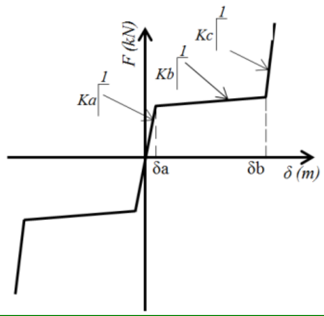


Stiffness	Foot Wall Side	Hanging Wall Side
Kt1	3794.4 kN/m	3794.4 / (1~5) kN/m
Kt2	37.944 kN/m	37.944 / (1~5) kN/m
δt_1	0.005 m	0.005 m

Figure 4. Stiffness diagram for soil transverse direct springs

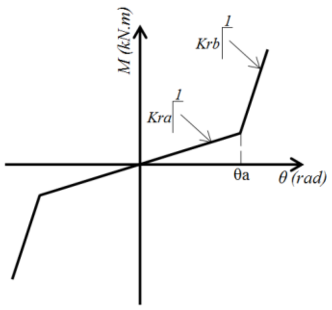
2.1.3. Modeling of joints

A joint is introduced in the pipe model by specifying two elements instead of one at nodes where joints are present. The forces and moments arising from the relative displacements and rotations of the two elements are computed according to the constitutive behavior as shown in figures 5 to 7 and obtained by laboratory tests, done by Kubota Corporation, Japan.



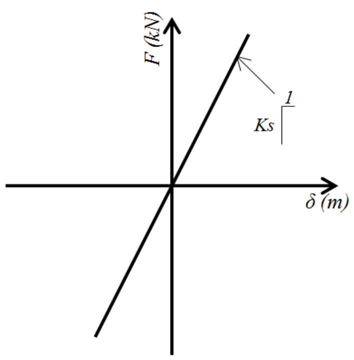
Stiffness	Foot Wall Side
Ka	980 kN/m
Kb	9.80 kN/m
Kc	980 kN/m
δa	0.001 m
δb	0.05 m

Figure 5. Axial Force – Joint Displacement Diagram



Stiffness	Foot Wall Side
Kra	12.7 kN.m/rad
Krb	108.7 kN.m/rad
θa	0.0855 rad

Figure 6. Bending Moment – Joint Angular Deflection Diagram



Stiffness	Foot Wall Side
Ks	196000 kN/m

Figure 7. Shearing Force – Joint Displacement Diagram

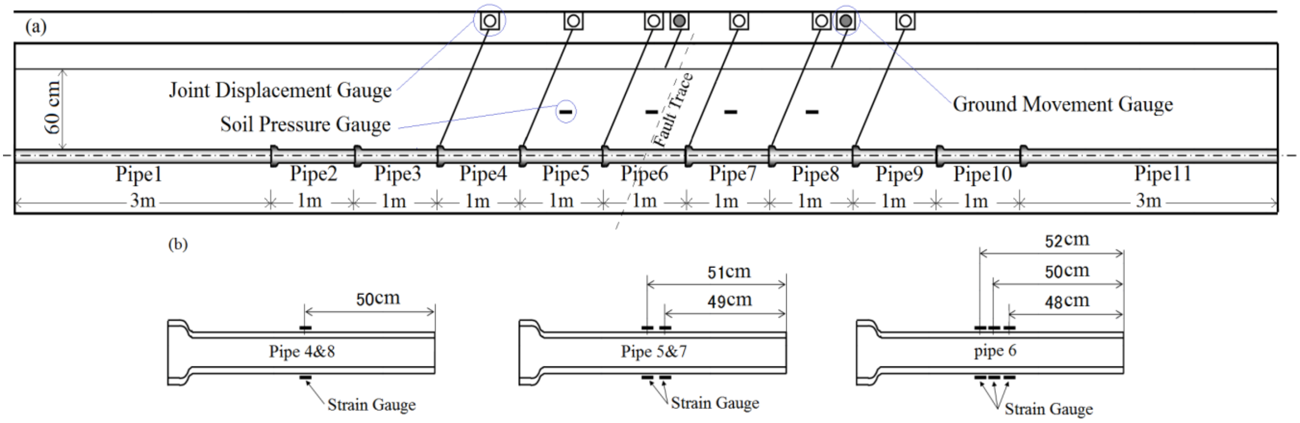


Figure 8. Layout of experimental test Facility (a), Strain gauges arrangement (b)

3. EXPERIMENTAL TESTS

The applicability of the method to simulate the behavior of an underground pipeline was verified by conducting an experiment using test facilities in Kubota Corporation, Japan. A Ductile Iron pipe as shown in the figure 8(a) is buried in a box filled with previously adopted soil. Both ends of the pipe are firmly fixed to a steel frame attached to the box, restricting both translations and rotations. The right-hand side of the box subsides by 30cm in vertical direction (35cm in fault trace direction) at 10cm increments, resulting in deformation of the pipe. Strain gauges are arranged along the pipe segments at locations indicated in figure 8(b). The joints are NS-Type earthquake resistant joints, with constitutive behavior as shown in figures 5 to 7.

4. VERIFICATION AND DISCUSSION

In order to find out appropriate reduction factor to reduce soil bearing resistance for use as its upward stiffness in computer-aided analyses, comprehensive numerical modeling have been done assuming this ratio varying from one to five and results of these analyses compared with experimental tests findings. Figures 9(a) and 9(b), respectively, depict entire pipeline displacement in Y direction and angular deflection in joints of pipeline for FEM analyses and experimental test at first step of fault movement in which hanging wall side moves 10cm in vertical direction (one-third of total 35cm in fault trace direction). While, similar information for second and third steps of fault movement is shown in figures 10 and 11, respecively.

In the first case, when reduction factor is one, stiffness of soil in upward and downward directions are assumed equal and as this factor goes up to five the stiffness of soil in upward direction is divided to this factor and reaches to 20 percent of its initial value.

These figures reveal that reduced stiffness of soil in upward direction leads to decrease in transverse load on pipe when moves relatively in this direction. Hence, accommodation of pipe with enforced ground deformation is provided by longer portion of pipeline. In other words, concentration of applied forces and deformations on the portion of pipeline in vicinity of fault-pipe intersection point is replaced by extension of enforced deformation to further segments and connection joints.

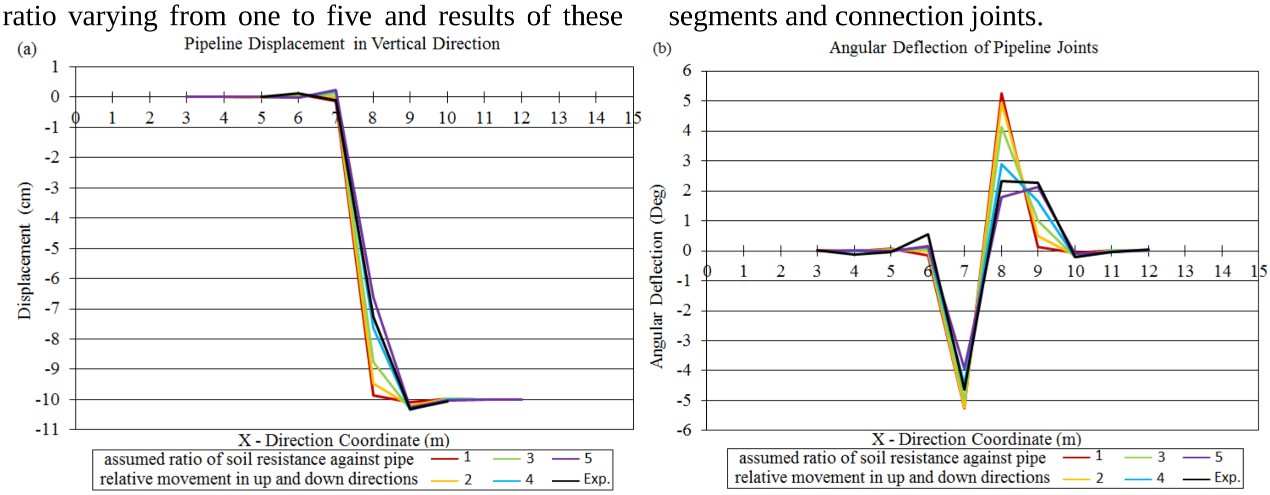


Figure 9. Results of FEM analysis and experimental test for first step of subsidence

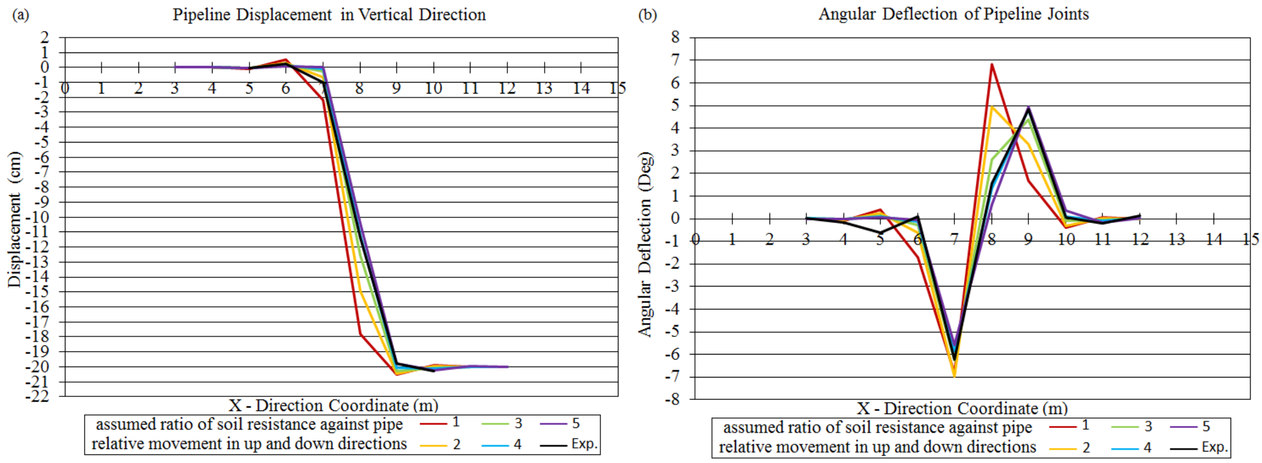


Figure 10. Results of FEM analysis and experimental test for second step of subsidence

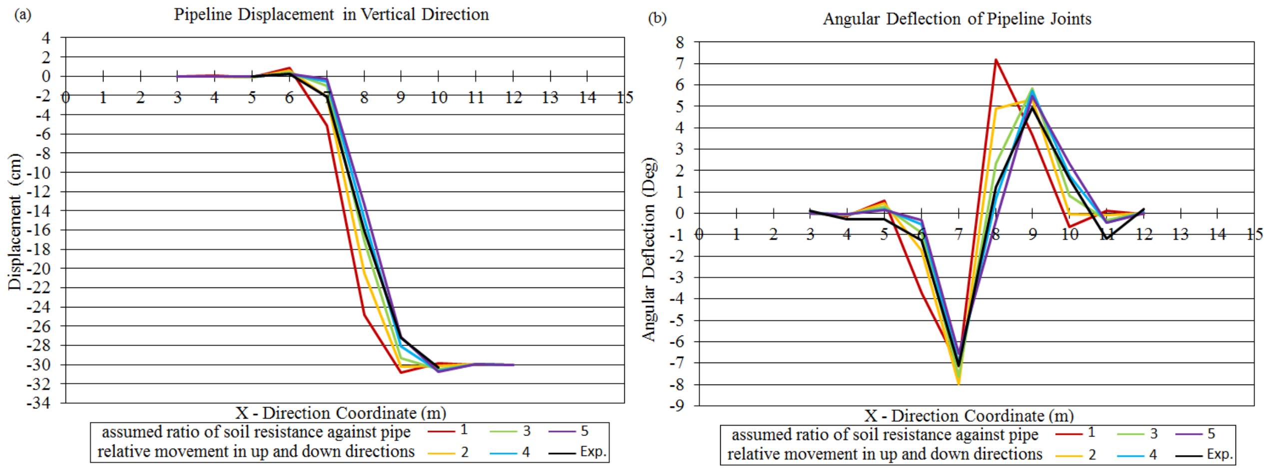


Figure 11. Results of FEM analysis and experimental test for third step of subsidence

Furthermore, comparison between results of computer-aided analyses and experimental tests reveals that minimum variant and closest correspondence in terms of both pipeline vertical displacement and angular deflection in joints of pipeline relates to the case in which soil stiffness in upward direction is considered one-fourth of downward one. Hence, hereafter we focus on comparison of pipeline behavior in cases with reduction factor equal to one and four.

As shown in numerical results plotted in figures 12 to 14, for larger reduction factor, upward force applied on pipe in footing wall side will be compensated by low rated downward soil force but in longer portion of pipeline in hanging wall side. This fact in numerical result diagrams is obvious as all internal force and moment diagrams are shifted to right by decreasing the stiffness of soil in upward direction to one-fourth of its initial value and their overspread in abscissa direction at hanging wall side.

Moreover, it can be realized, for case with equal soil stiffness in upward and downward directions, pipe acts as beam with both ends fixed and has almost symmetric reactions in terms of produced transverse force and bending moment in whole pipeline and connection joints.

While, for the case with reduced stiffness of soil in upward direction, behavior of pipe changes to fixed-pined beam and its reaction is no longer symmetric and the footing wall side of fault works as fixed end of beam with larger restriction against rotation. So, pipeline elements including the segments and join connections have to carry large moments and transverse force in its vicinity.

As shown in figures 12 to 14, ratio of produced internal attempts regarding bending moment in footing wall side is one and a half time of corresponding values in hanging wall side and this ratio is fixed for all three steps of fault movement in which fault subsides 10, 20 and 30cm in vertical direction (respectively, one-third, two-third and whole of 35cm in fault trace direction).

Results of this study suggested that ignoring reduction of soil stiffness in upward direction for shallow depths, often used for burial of pipes, in addition to incorrect knowledge on interaction of pipe and surrounding soil, causes overestimated analyses and uneconomical designs for one of most seismic-vulnerable engineering systems.

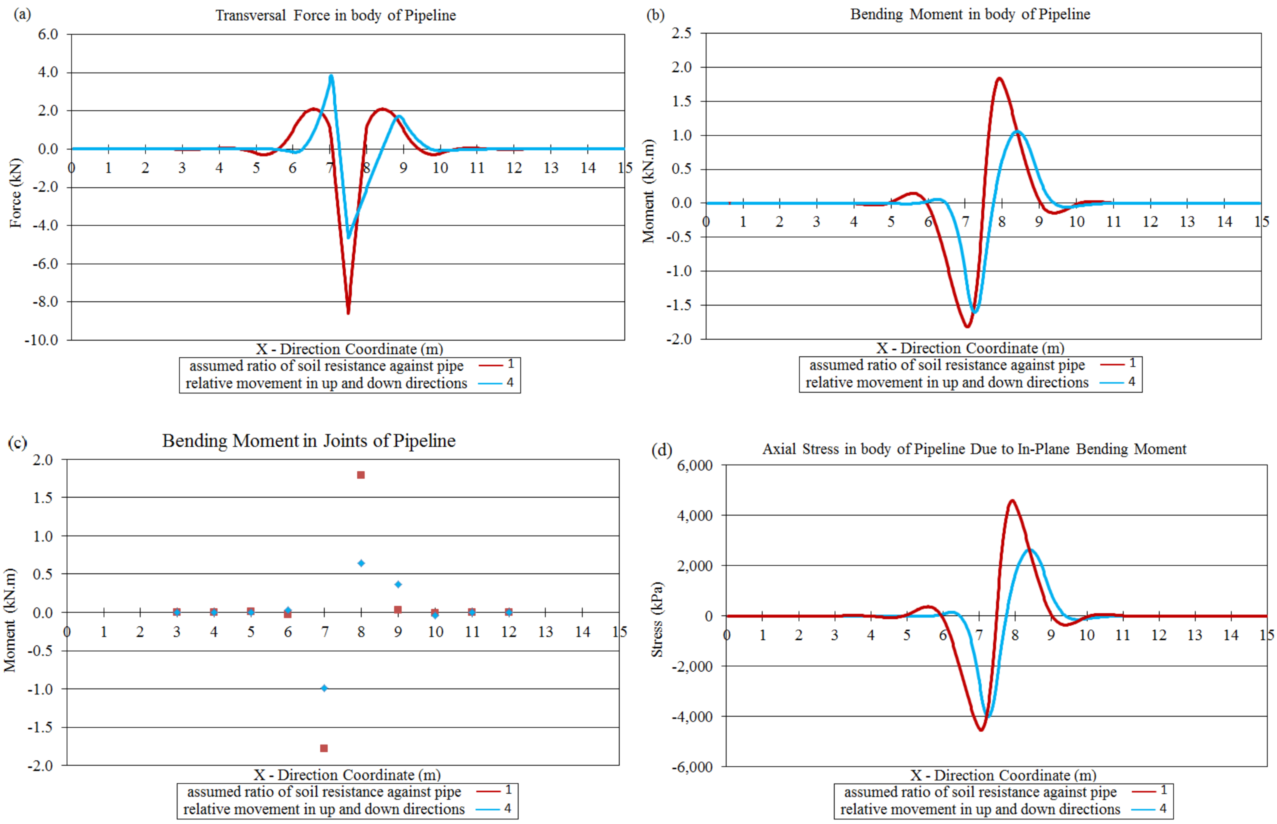


Figure 12. Results of FEM analysis and experimental test for third step of subsidence

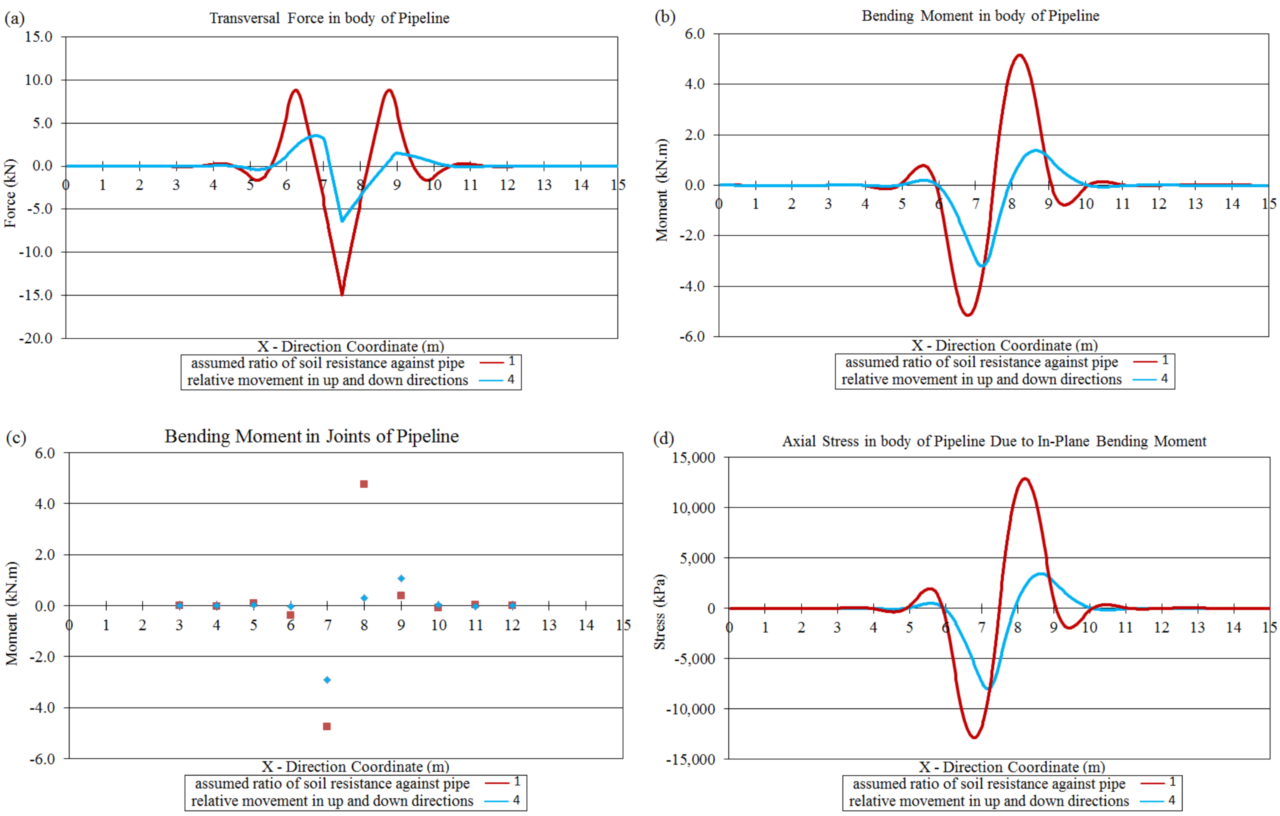


Figure 13. Results of FEM analysis and experimental test for third step of subsidence

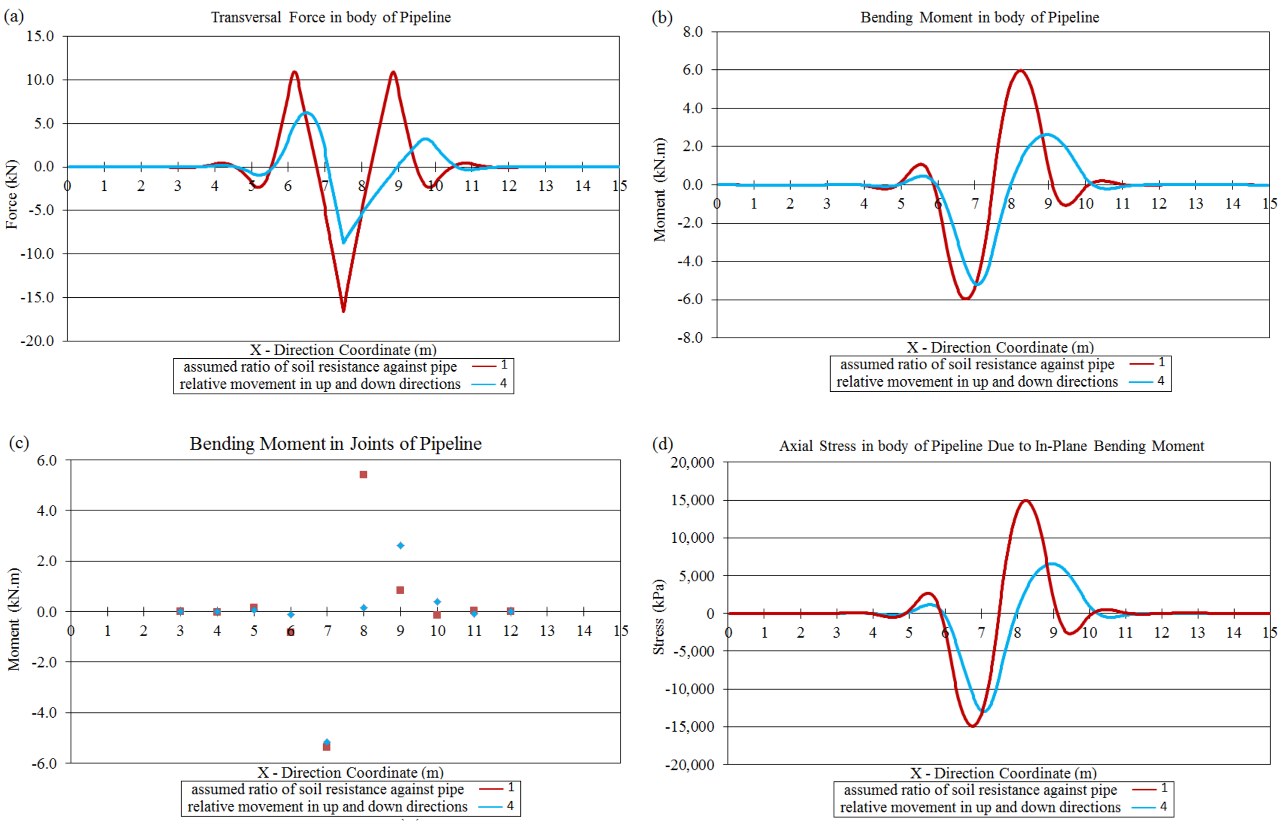


Figure 14. Results of FEM analysis and experimental test for third step of subsidence

6. CONCLUSIONS

This study investigates the applicability of introduced simple method to estimate the transverse vertical load on buried pipelines crossing dip faults by considering different behavior of soil in two sides of subsidence trace. Numerical evaluation of this load is based on simple concept of equality of soil stiffness in downward direction to subgrade reaction times to interfaced area of soil and pipe projection in horizontal plane and multiplied to an appropriate reduction factor as its upward stiffness. To find appropriate value as reduction factor, comprehensive numerical modeling has been done with varying reduction factor from one to five and results of computer-aided analyses compared with experimental tests findings.

Furthermore, It is realized, reduction in upward stiffness of soil may reduce it to fixed-pinned beam with relative large moments and transverse force in pipeline elements in vicinity of stiffer soil wall side. While for the case with equal soil stiffness in upward and downward directions, pipe acts as beam with both ends fixed and has almost symmetric reactions in terms of produced transverse force and bending moment in whole pipeline and connection joints.

In terms of pipeline behavior, this study suggests that ignoring reduction of soil stiffness in upward direction causes incorrect knowledge on soil-pipe interaction and overestimated design of pipelines. However, since the relationship used herein for numerical evaluation of soil stiffness depends on sub-grade reaction, to confirm the consistency of specified numbers as results of this study such as soil reduction factor, it is needed to repeat the analyses and experimental tests for other soils with different sub-grade reaction.

ACKNOWLEDGMENT: The cooperation of Ductile Iron Pipe R&D Department of Kubota Corporation, Japan in providing experimental data for Ductile Iron pipes and joints is highly appreciated. This research would not have been possible without it.

REFERENCES

1) Trifonov OV., Cherniy VP.: A semi-analytical approach to a nonlinear stress-strain analysis of buried steel pipelines crossing active faults. *Soil Dynamic Earthquake Engineering*, 1-11. 2010.

2) Vazouras P., Karamanos S.A., Dakoulas P.: Finite element analysis of buried steel pipelines under strike-slip fault displacements. *Soil Dynamic Earthquake Engineering*, 30(2010), 1361-1376. 2010.

3) Vougioukas, E.A., Carydis, P.G.: Performance of buried pipelines, subjected to fault movement, *Tenth World Conference on Earthquake Engineering*, 1992.

4) Ivanov R., Takada S., Morita N.: Analytical assessment of the vulnerability of underground jointed PVC pipelines to fault displacements, Paper No. 613, *Thirteenth World Conference on Earthquake Engineering*, 2004.
5) Manual for seismic design of gas distribution pipelines, *Japan Gas Association*, 1982.
6) Ivanov R., Takada S.: Assessment of the vulnerability of jointed ductile iron pipeline crossing active faults, *Japan Society of Civil Engineering, Journal of Earthquake Engineering*, 2003.
7) Liu A., Takada S., Hu Y.: A shell model with an equivalent boundary for buried pipelines under the fault movement, Paper No. 613, *Thirteenth World Conference on Earthquake Engineering*, 2004.
8) Erami, M.H., Miyajima, M., Fallahi. A.: A State–of–the–art Review on Fault Crossing Pipeline Analysis, Paper No. 10-2228, *Sixth International Conference on Seismology and Earthquake Engineering, Iran, 2011*.
9) Seismic Guidelines for Water Pipelines, *American Lifelines Alliance*, 2005.
10) Design manual for joints of ductile iron pipe type NS, S II and S, Japan Ductile Iron Pipe Association (In Japanese).