SEISMIC DESIGN APPROACH FOR STEEL PIPELINES CROSSING ACTIVE FAULTS

N. Hasegawa[1*], T. Imai[1], J. Kitagawa[2] and T. Koike[3]

[1]*Water Pipeline Engineering Department, Engineering Section, JFE Engineering Corporation*

[2]*Graduate student, Division of Civil Engineering, Kyoto University*

[3]*Professor, Division of Civil Engineering, Kyoto University*

ABSTRACT :

Because an extremely large number of active faults exceeding 2000 exist in the Japanese archipelago, it is difficult to eliminate the possibility that water pipelines and other lifeline systems, which are linearly long-extended structures, may cross faults. Thus, earthquake-proof countermeasures for fault crossing pipelines have been desired. There are many previous studies on large deformation behavior of fault-crossing pipelines not only in empirical approach but also in numerical method. However, little research has examined construction methods for avoiding rupture of these pipelines. In the present study, "Steel Pipe for crossing Fault (SPF)" was developed as a construction countermeasure for water pipelines that must cross faults. One pair of the developed SPF's which are located across the fault line can avoid extreme shear deformation of the pipeline near the fault-crossing zone, and thereby prevents buckling or tear failure at the fault-crossing point. This report presents seismic performance of SPF and proposes a seismic design method for fault-crossing pipelines using SPF. The results of a study show the optimum arrangement of SPF's.

Keywords: Pipeline, Buckling, Fault, Seismic Design.

1. INTRODUCTION

The Off the Pacific Coast of Tohoku Earthquake of 2011, which was a huge earthquake with a moment magnitude (Mw) of 9.0, inflicted tremendous tsunami damage on the coastal areas in the Tohoku region. Since the earthquake may also have affected the overall balance of stress in the Earth's crust forming the Japanese Archipelago, there is concern about possible effects of the earthquake on inland seismic activity in the coming years. Active faults existing in many parts of the country are potential high-risk spots where inland earthquakes may occur, and those faults may even cause fault displacements at the ground surface.

Buried pipelines crossing unidentified faults may undergo stretching or buckling of the pipelines depending on the type of fault (normal or reverse). In any case, in the event of fault movement across a pipeline, the cross section of the pipeline may become substantially smaller, or, depending on the circumstances, pipe damage or even leakage due to cracking may result.

* Presenter and Corresponding author: Email: hasegawa-nobuhiro@jfe-eng.co.jp

In Japan, seismic design methods for buried pipelines to protect them from earthquake ground motions were revised extensively in the wake of the 1995 Hyogoken Nanbu Earthquake,[1)2)] and seismic design methods (waterworks and gas pipelines) for protection from ground liquefaction were also established. Seismic design methods, however, for protection from fault displacement have not yet been established.

The authors have developed a seismic design method for fault-crossing water supply pipelines using steel pipes designed specifically for fault crossing applications. This report briefly introduces newly developed steel pipes called "SPF" (Steel Pipe for crossing Fault) and proposes a new seismic design method using SPFs that can be used to protect fault-crossing steel pipelines.

2. DAMAGE TO FAULT-CROSSING PIPELINES

The Chi-chi Earthquake of 1999 in Taiwan caused fault displacements of up to 12 m and significant pipeline damage as shown in Figure 1. The pipe damage shown in Figure 1 is an example of damage to a buried steel pipeline crossing a fault. As shown, the pipe was bent plastically in the shape of the letter "Z." For the purpose of identifying the mechanism of Z-shaped plastic deformation, a finite element analysis of the pipeline–soil system as shown in Figure 2 was conducted. The pipeline and the soil were modeled with shell elements and solid elements, respectively, and forced displacement was given so that fault displacement occurs in the direction indicated by the arrow. In the analysis, as shown in Figure 2, buckling occurred symmetrically on both sides of the fault at certain distances from the fault plane. The fault cross section does not necessarily show deformation, and the analytical results were consistent with the observation results shown in Figure 2.The analytical results indicate that if fault displacement occurs, the pipeline rotates about the fault plane. When this occurs, soil shear force occurs along the fault plane. Since, however, the stiffness of the pipe is sufficiently large compared with the soil shear force, buckling does not occur at the shear plane. Because of fault displacement, however, rotating force acts on the pipe so that bending occurs on both sides of the fault plane at points certain distances away from the fault plane. When the full plastic moment is reached at the points where the maximum bending moment occurs, buckling begins to occur so that plastic hinges are formed. As shown in Figure 2, bending deformation is concentrated only at the plastic hinges. It is thought, therefore, that the most effective method is to take measures to absorb bending force at the points where the maximum bending moment occurs.

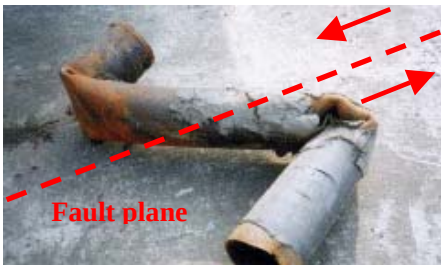


Figure 1: Example of pipeline damage (Chi-Chi Earthquake, Taiwan)

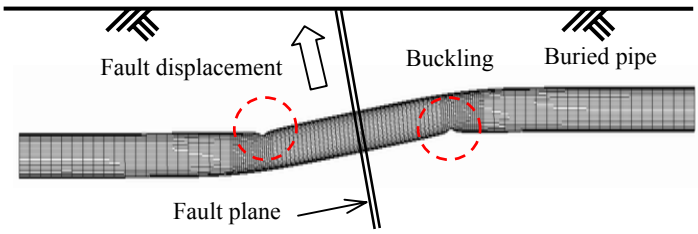
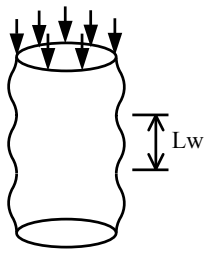


Figure 2: Deformation of buried pipeline caused by fault displacement

3. OUTLINE OF SPF

In axial compression buckling of a cylindrical shell like a steel pipe, the effect of initial irregularities (e.g., slight asymmetries, etc.) increases as wall thickness decreases. Buckling patterns and buckling loads vary depending on the location and degree of initial irregularity. On both sides of a reverse fault as shown in Figure 2, the pipeline sustains compression and bending deformation. It is difficult, however, to predict the location of buckling and subsequent deformation because initial irregularities of pipes vary from pipe to pipe. If, however, the pipe is shaped in advance so as to induce deformation in a particular region, it is possible to concentrate deformation in that region.

As an initial deformation pattern, the SPF[3)] is given a wavy shape, which is the mode of deformation that occurs when a cylindrical shell is compressed axially. Wave width was determined as a multiple of the wavelength determined according to Timoshenko's buckling half-wavelength theory,[4)] and wave height as a multiple of wall thickness, and the optimum configuration was selected through FEM analysis and experiment.



Theoretical formula for buckling half-wavelength (Lw)

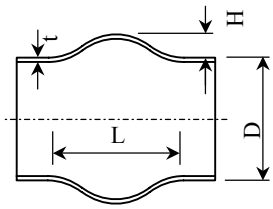
$$Lw = 1.72\sqrt{r \cdot t} \qquad (1)$$

where,

r: mid-thickness radius of pipe

t: wall thickness

Figure 3: Deformation mode of cylindrical shell under axial compression



Outside diameter of pipe (D)

Wave width (L) $\quad L = 2n \cdot Lw \qquad (2)$

Wave height (H) $\quad H = m \cdot t \qquad (3)$

where, n, m: integers

Figure 4: Specification of designed buckling pattern

4. DESIGN METHOD FOR FAULT-CROSSING PIPELINE

A number of studies have been reported concerning the behavior of fault-crossing pipelines. As an example of a seismic design method, Takada et al.[6)] proposed a simple method for calculating the maximum strain in a pipeline. Design methods like this calculate the maximum strain in a pipeline due to fault displacement, but they do not deal with how to prevent pipeline damage due to fault displacement. Guideline of Seismic Design for Water Facilities[2)] as amended in 2009 shows an example of a multiple-pipe installation with flexible joints as a method of fault-crossing pipeline protection. There is as yet no established design method, however, that includes post-installation protection measures. This paper proposes a new seismic design method

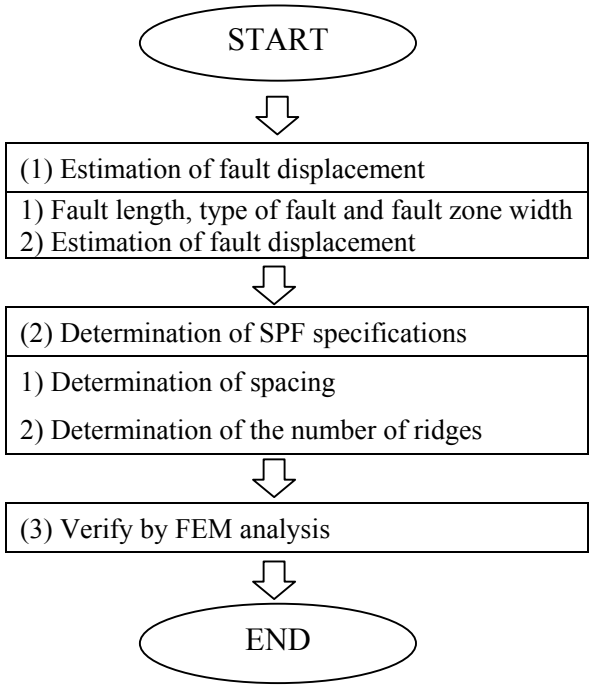


Figure 5: Design flow

applicable to the SPFs developed by the authors as a means of protecting fault-crossing pipelines.

Figure 5 shows the design flow of the proposed method for designing fault-crossing pipelines.

4.1. Estimation of fault displacement

The width of the fault zone (width of the shear zone) to be crossed by a buried pipeline and the amount of fault displacement are calculated as follows:

Fault zone width (shear zone width)[6)]

$$W = 1.65 \times 10^{-3} L^{1.15} \tag{4}$$

where, W: shear zone width (m)

L: fault length (m)

Fault displacement estimated formula[7)]

$$LogD\max = 1.16Mw - 7.69 \tag{5}$$

where, D_{max}: maximum displacement of fault (m)

Mw: moment magnitude

4.2. Determination of construction spacing of SPF

As mentioned in Chapter 2, when a fault occurs in the reverse direction, a pipeline crossing that fault is bent on both sides of the fault plane at points certain distances away from the fault plane. It is thought that when such bending occurs, buckling locations are dependent on the stiffness of the soil surrounding the pipeline. Construction spacing of SPF, therefore, should be determined according to the buckling locations under the design conditions determined by fault displacement, fault displacement direction, soil stiffness and pipeline stiffness.

One way to determine spacing requirements is to determine the location of the maximum bending moment through FEM analysis because pipe deformation is concentrated in the plastic hinge zones. Since, however, FEM analysis requires a considerable amount of time, in this study the optimum spacing is determined by deriving a simple formula for spacing calculation. Figure 6 shows a simple pipeline model including an SPF in the case where fault displacement occurs.

As shown in Figure 9, if fault displacement Δy occurs, bending moment M acts at the center of the pipe in this simple model. This fault displacement Δy is converted to the bending moment M by rotating a pipe with spacing L by angle θ. When the pipe within spacing L rotates, soil reaction F acts so that tensile force P occurs between the pipe segment and the adjoining pipe segments. It is further assumed that the SPF acts as a rotational spring and receives the

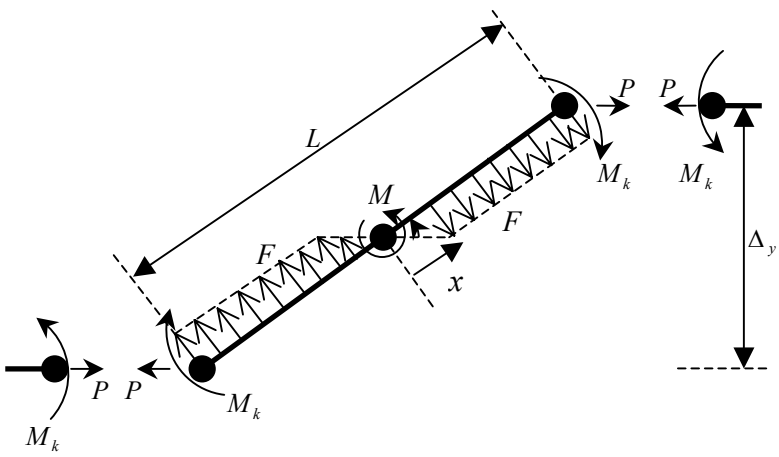


Figure 6: Simple pipeline model including SPF

bending moment *Mk*. The overall equilibrium condition can be satisfied by considering the tensile force *P* from the adjoining pipe segments. Soil reaction is assumed to always act in the direction perpendicular to the pipe axis.

For the purpose of simple formula derivation, it is assumed that the pipeline is a beam on an elastic foundation. If the pipeline is divided into a spring support section and a uniformly distributed load section as in Figure 9, the basic equation can be expressed by using Eq. (6) and Eq. (7): where *v (x)* is the displacement in the direction perpendicular to the pipe axis; EI, bending stiffness; *Kv*, the soil spring coefficient in the direction perpendicular to the pipe axis, which is assumed to be uniform in the vertical direction.

$$EI\frac{d^4v}{dx^4} = F = K_V x\sin\theta \qquad 0 \le x \le \frac{\Delta_0}{\sin\theta} \tag{6}$$

$$EI\frac{d^4v}{dx^4} = F = K_V\Delta_0 \qquad \frac{\Delta_0}{\sin\theta} \le x \le \frac{L}{2} \tag{7}$$

The boundary conditions are expressed as follows:

v, v', v'' and v''' are continuous if $x = \dfrac{\Delta_0}{\sin\theta}$

$$EIv'''\left(\frac{L}{2}\right) = -Q\left(\frac{L}{2}\right) = -P\sin\theta \tag{8}$$

$$EIv''\left(\frac{L}{2}\right) = -M\left(\frac{L}{2}\right) = M_k \tag{9}$$

Stress distribution perpendicular to the pipe axis, σ_M/σ_B, can be expressed by Eq. (10) and Eq. (11). The ratio σ_M/σ_B is the ratio between the bending moment perpendicular to the pipe axis and the buckling stress in the section of length x from the mid-point of the spacing *L*. If σ_M/σ_B exceeds −1, a fully plastic state occurs. It is therefore possible to determine which part of the section within the spacing *L* is in a fully plastic state. From this equation, spacing *L* is assumed and the validity of the spacing is evaluated in view of the fully plastic region in that section.

$$IF \quad 0 \le \frac{2x}{L} \le \frac{2\Delta_0}{L\sin\theta}$$

$$\frac{\sigma_M}{\sigma_B} = \frac{1}{1.27M_Y}\left[\begin{array}{l} -\frac{1}{48}K_V L^3\sin\theta\cdot\left(\frac{2x}{L}\right)^3 + \frac{1}{8}K_V L^2\Delta_0\left\{\left(2-\frac{2\Delta_0}{L\sin\theta}\right)\cdot\left(\frac{2x}{L}\right)-1+\frac{1}{3}\left(\frac{2\Delta_0}{L\sin\theta}\right)^2\right\} \\ -\frac{1}{2}PL\sin\theta\cdot\left(1-\frac{2x}{L}\right) \end{array}\right] - \frac{M_k}{M_P}$$

$$IF \quad \frac{2\Delta_0}{L\sin\theta} \le \frac{2x}{L} \le 1 \tag{10}$$

$$\frac{\sigma_M}{\sigma_B} = \frac{1}{1.27M_Y}\left[-\frac{1}{8}K_V L^2\Delta_0\left(1-\frac{2x}{L}\right)^2 - \frac{1}{2}PL\sin\theta\cdot\left(1-\frac{2x}{L}\right)\right] - \frac{M_k}{M_P} \tag{11}$$

where, σ_M: bending stress in perpendicular direction σ_B: buckling stress

Δ_0: soil yield displacement in perpendicular direction

Kv: soil spring coefficient in perpendicular direction

My: full plasticity moment *P*: tensile force from adjoining pipe segments

Figure 7 shows relationship between fault displacement and allowable bending angle. The approximate spacing can decide from Figure 7.

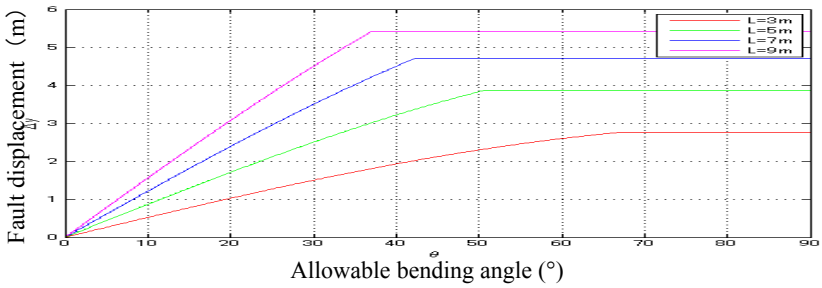
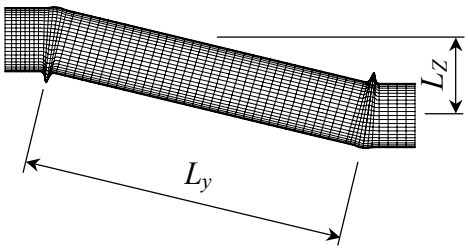


Figure 7: Relationship between fault displacement and allowable bending angle

4.3. Determination of number of buckling patterns

The bending angle is calculated from fault displacement and spacing by using Eq. (12). In view of the relationship between the diameter/wall thickness ratio (*D/t*) and the inner wall contact angle shown in Figure 8, it was decided to use 12° as the allowable bending angle per buckling pattern of the SPF. It is a conservative value because the allowable bending angle for steel pipes for water supply applications within a standard *D/t* range of 100.6 to 113.3 is about 13°. As shown in Figure 12, however, a larger allowable bending angle can also be used by making the *D/t* ratio smaller.



$$\theta = \sin^{-1}\left(\frac{Lz}{Ly}\right) \tag{12}$$

where, θ: bending angle (°)

L_y: distance between plastic hinges (m)

L_z: vertical fault displacement (m)

Figure 8: Design method for the required number of buckling pattern

If the bending angle becomes larger than the allowable bending angle because of the relationship between fault displacement and spacing, the number of buckling patterns may be increased. If there are two or more buckling patterns, when the inner wall of the first buckling pattern have come into contact, reaction force increases so that deformation spreads toward the second and subsequent buckling patterns. Figure 10 verifies how a real pipe (Outside diameter of 60.5 *mm*) is deformed progressively. Figure 11 shows the result of FEM analysis verification conducted under the same conditions.

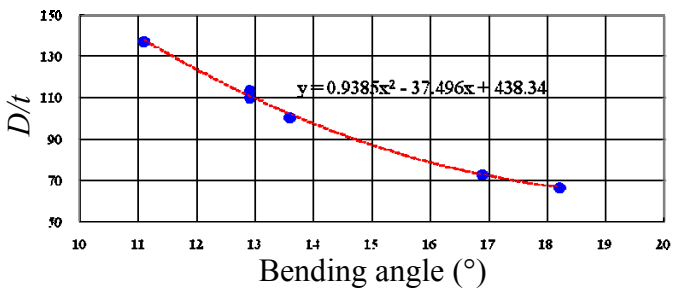


Figure 9: Relationship between D/t and inner wall contact angle

Figure:10 Verification of progressive deformability (real pipe)

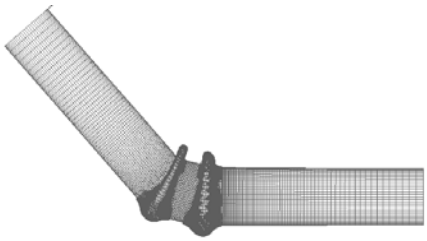


Figure 11: Verification of progressive deformability (FEM analysis)

5. EXAMPLE OF SPF APPLICATION

This chapter introduces an example of application of the newly developed seismic design method using SPFs as a means of fault-crossing pipeline protection.

5.1. Case study conditions

Figure 12 shows the fault under consideration, and Table 2 shows the case study conditions.

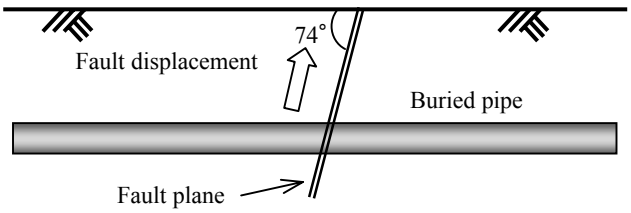


Figure 12: Model of case study

Table 2: Basic conditions for case study.

Steel pipe	Nominal diameter	2400A
	Wall thickness	24mm
	Material	SS400
	Young's modulus	2.0×10^5 N/mm^2
	Yield stress	225 N/mm^2
Soil	Young's modulus	25 N/mm^2
	Poisson's ratio	0.49
	Cohesion	50 kPa
	Internal friction angle	0 °
Fault	Fault type	Reverse
	Fault angle	74 degree
	Fault displacement	1.44m

5.2. Modeling of pipeline

As shown in Figure 13, in pipeline modeling, the soil is modeled with solid elements, and the pipe with shell elements. The soil and the pipeline are defined as being in contact, and a total pipeline length of 120 *m* is assumed so that the ends are outside the zone of influence of fault displacement.

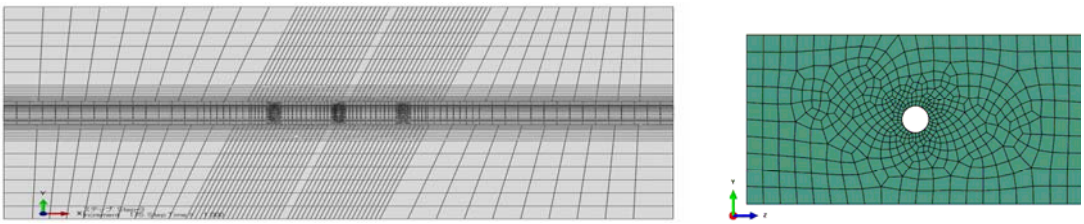


Figure 13: Modeling of pipeline

5.3. Performance verification by FEM analysis

The wave-shaped sections were located according to the spacing *L* of 7 *m* determined from Figure 7, and the bending capacity of the SPF was verified through FEM analysis by varying fault

displacement. As shown in Figure 14, the analytical results show that bending moment acted on the buckling patterns, and deformation is concentrated only in the buckling pattern zones. As shown in Figure 14, the bending angle corresponding to the fault displacement of 1.44 *m* is 11.2°, which is within the allowable limit of the bending angle (12°). As shown in Figure 15, it has also been confirmed that the inner surfaces of the pipe did not come into contact, indicating that the bending angle was within the allowable limit.

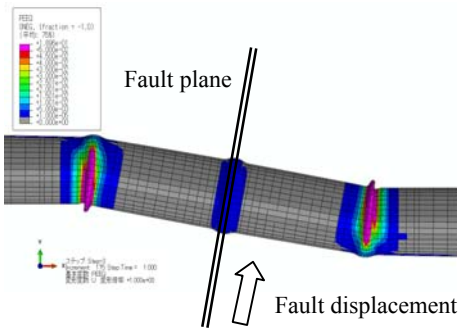


Figure 14: Deformation of designed buckling pattern in the case study

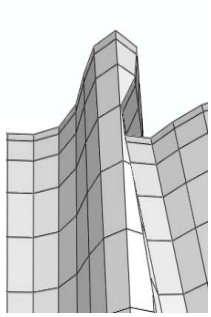


Figure 15: Deformaition of designed buckling patterns

6. CONCLUSION

This report has briefly described SPFs, steel pipes developed for fault-crossing applications, proposed a seismic design method for fault-crossing pipeline protection using SPFs, and introduced an example of its application.

SPFs are designed to follow very large deformation and maintain the cross section to carry water even after deformation in order to keep water supply lifeline facilities functional even in the event of an earthquake by making effective use of the elastoplastic deformation capacity of steel pipes. Because the allowable limit is set to have a sufficient margin before reaching the critical value, leakage will not occur even if an unexpectedly large amount of displacement occurs. It is therefore believed that SPFs have made it possible to establish an environment for taking purpose-specific seismic safety measures even for fault-crossing pipelines for which effective seismic safety measures could not be taken in the past. It is the authors' sincere hope that the newly developed method will help make ongoing nationwide efforts to enhance the seismic safety of waterworks more effective.

References

1) Japan Gas Association(2007): Seismic design guidelines for high pressure gas pipelines against liquefaction (in Japanese).
2) Japan Water Works Association(2009): Guideline of Seismic Design for Water Facilities (in Japanese).
3) Hasegawa, N., Imai, T. and Suzuki, N.(2009): "Development of high seismic performance pipe for crossing active faults," The Sixth Japan–US–Taiwan Workshop on Water System Seismic Practice.
4) Timoshenko, S.(1954): Zakutsu Riron (Jap. trans.; translated by Namikawa, K., Naka, T. and Hisada, T.), Corona Publishing.
5) Takada, S., Hassani, N. and Fukuda, K.(2001): "Proposed design method for fault-crossing buried pipelines" (in Japanese), Proceedings of JSCE, No. 668/I54, pp. 187–194.
6) Kataoka, S. and Kusakabe, T.(2005): "Relationship between the scale and type of inland earthquakes and characteristics of surface earthquake faults" (in Japanese), Proceedings of JSCE, No. 801/I-73, pp. 21–32.
7) Kanaori, Y.(2001): "How far does the influence of faults reach?" (in Japanese), Jour. Japan Soc. Eng. Geol., Vol. 41, No. 6, pp. 323–332.