SEISMIC PERFORMANCE ASSESSMENT OF EXPANSION JOINTS FOR WATER LIFELINES

T. HIGASHIDE
University of Kyoto, Japan

T. YABUGUCHI & T. IMAI
JFE Engineering Co., Yokohama, Japan

T. KOIKE
University of Kyoto, Japan

SUMMARY:
In the 2011 Great East Japan Earthquake, the largest water leakage flows occurred at failed expansion joints in 2400mm and 1200mm diameter water pipelines in Miyagi Prefecture. The damage mechanism of buried expansion joints was investigated by site damage inspections and seismic response analyses, which suggested that the expansion joints had absorbed certain settlement before the earthquake, and as a result, the seismic shaking triggered expansion joint failure. This study proposes a new seismic design method for expansion joints, especially those used in arc-welded steel pipelines.

Keywords: Great East Japan Earthquake, expansion joint, pipeline, riser, seismic design

1. INTRODUCTION

Many water pipelines were damaged in the 2011 Great East Japan Earthquake. In particular, buried expansion joints used in large diameter water main lines were broken, resulting in large-scale leakage and suspension of water service for several weeks.

Generally, buried water pipelines suffer relative vertical displacement, which is forced by uneven settlement between the pipeline itself and the structural facility housing the control equipment, and relative axial displacement caused by ground shaking. Both types of relative displacement are absorbed by expansion joints, which are installed in the pipeline near the structural facility. Especially in water main lifelines, expansion joints are used not only in segmented pipelines but also in arc-welded pipelines.

In this study, based on site observation of damaged joints, the failure mechanism of buried expansion joints was investigated by site damage inspections and seismic response analyses. The first event caused large-scale leakage from a pair of expansion joints installed at the outlet of a concrete encased under-crossing structure. The second event of leakage damage from an expansion joint appeared approximately one month later after the main shock. Both results had the common characteristics that there was no typical ground deformation which could produce failure of the expansion joints, and there was no additional deformation allowance for the seismic response of the joint because the joint had absorbed a certain settlement before the earthquake. These investigations suggest the possibility that buried expansion joints may change from safety devices to potential defects that can cause leakage failure under seismic loading.

This study proposes a new seismic design method for expansion joints, especially those used in arc-welded steel pipelines. The new method describes the adequate allocation of expansion joints and additional deformation allowances for avoiding pull-out failure due to seismic displacement.

2. SEISMIC DAMAGE OF EXPANSION JOINTS IN WATER PIPELINES

Table 2.1. summarizes the damage data of buried large diameter water pipelines in the 2011 Great East Japan Earthquake. The typical characteristics are

1) leakage failure from the expansion joints;
2) leakage from old joints with poor welding quality dating from before 1965;
3) expansion joint failure between the concrete structure and surrounding soil which had already undergone certain excessive relative displacement; and
4) wrong application of expansion joints in soft ground based on the former JWWA design guideline.

Among these, the largest water leakage flows occurred at failed expansion joints in 2400mm and 1200mm diameter water pipelines in Miyagi Prefecture. Both pipelines are located in the southern part of Miyagi Prefecture, as shown in Figure 2.1., where the JMA seismic intensity in the March 11th earthquake was 6+, or approximately 250~400 cm/sec^2. Figure 2.2. shows the strong ground motion at Shiroishi (nearest point to the sites) in the March 11th main shock and April 7th aftershock, respectively. As both pipelines are pressurized trunk lines which convey water to demand nodes, the pipe segments were carefully jointed to take into account possible uneven settlement due to various soil conditions along the pipe route.

Table 2.1. Damage to buried large diameter water pipelines in 2011 Great East Japan Earthquake.

Location	Diameter	Damage descriptions
Miyagi Pref.	2400mm	Leakage and joint separation damages occur at the expansion joints of the both ends of under-crossing concrete structure.
Miyagi Pref.	1200mm	Leakage occurs at the after shock after one month of the main shock at the expansion joint located between the valve vault and the concrete covered riser pipe.
Miyagi Pref.	1000mm	Separation of the expansion joint between the concrete structures
Miyagi Pref.	700mm	Leakage from the repaired welded portion
Fukushima Pref.	2000mm	Separations of 12 expansion joints in the liquefaction area
Ibaraki Pref.	1100mm	Tie rod failure of the expansion joint by the excessive tension load caused by the ground movement
Ibaraki Pref.	various	Expansion joint failure at 25 locations in the liquefied zone of the purification plant
Kanagawa Pref.	3100mm	Leakage of 3 expansion joints which were designed with the SUS bellows type expansion joint based on the old design guideline
Kanagawa Pref.	600mm	Leakage from the welded joint crack. The same types of accidents have been experienced along this pipeline.

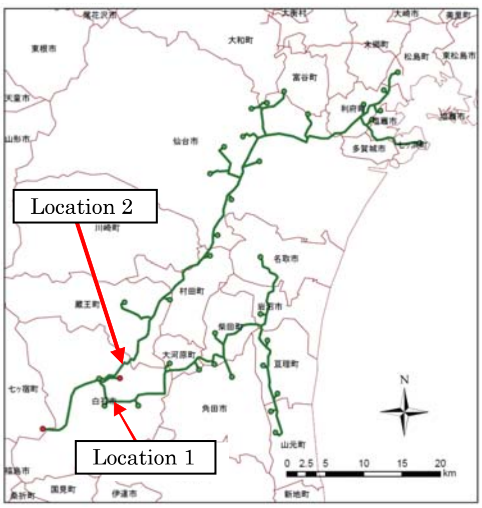


Figure 2.1. Locations of leakage accidents

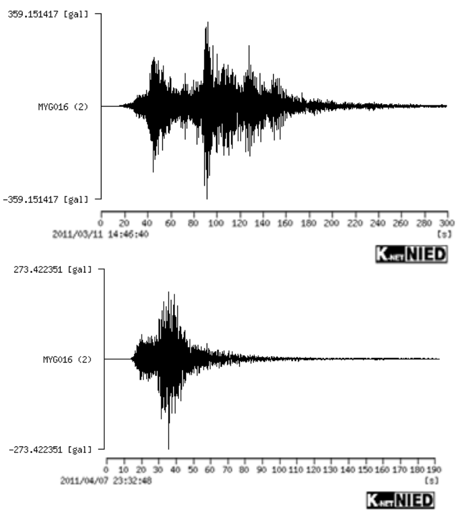


Figure 2.2. Strong ground motion at Shiroishi (MYG016) in main shock (2011.3.11) and after shock (2011.4.7)

3. FAILURE MECHANISM OF THE EXPANSION JOINTS

3.1. Expansion joints under-crossing stream line

Photo 3.1. shows the large-scale water leakage from the expansion joint in the 2400mm diameter water pipeline immediately after the main shock. The accident occurred at both sides of the concrete encased pipeline under-crossing a water stream, as shown in Figure 3.1. It must be noted that this leakage occurred at the same time from both expansion joints. The concrete encased structure moved 700mm in the anticlockwise direction at site A and 100mm at site D.

Photo 3.1. Water leakage from expansion joint

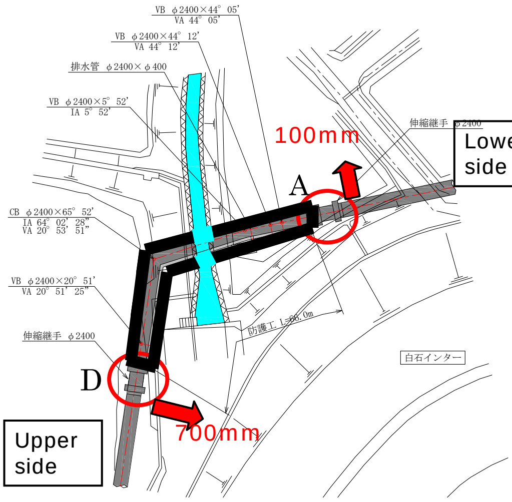


Figure 3.1. Location map of expansion joints under-crossing stream line

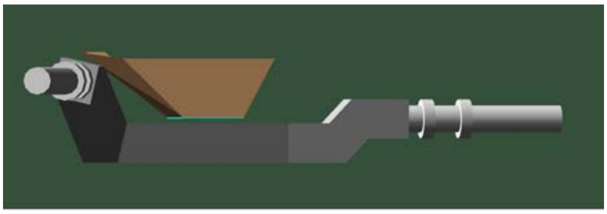


Figure 3.2. Three-dimensional illustration of under-crossing concrete encased structure

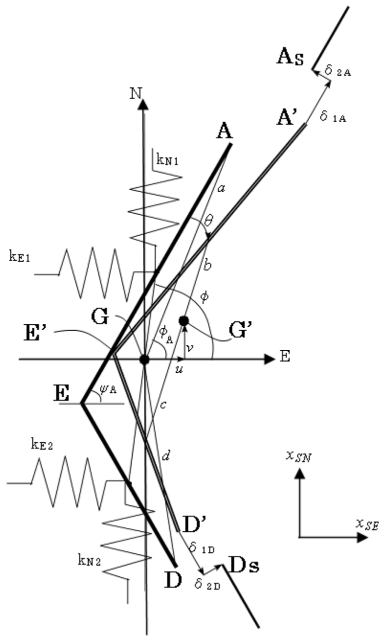


Figure 3.3. Two-dimensional simplified analytical model of under-crossing concrete encased structure

According to site observations, there were no ground changes triggering liquefaction, ground slippage or uneven settlement. As shown in Figure 3.2., this under-crossing concrete encased structure has an unstable configuration and is not symmetrical even in the two-dimensional plan view.

In order to investigate the failure mechanism of the two expansion joints, a configuration describing a two-dimensional simplified model of the under-crossing concrete encased structure is introduced, as shown in Figure 3.3. The gravity point of the structural model is the origin of this figure, and the spring moduli are adopted to simulate the soil-structural interaction of the buried structure. The direction of the coordinate system is identical to the global direction. Since the expansion joints are structurally separated from the concrete encased structure, joint failure occurs when the relative displacement between the concrete encased structure and its corresponding stretching pipe exceeds the critical displacement in the axial direction and/or transverse direction. To assess this criterion, the relative displacements at the end points A and D are estimated by the following formula:

$$A=\begin{pmatrix} a\cos\phi_A \\ a\sin\phi_A \end{pmatrix} \ , \ A'=\begin{pmatrix} u+a\cos(\phi_A-\theta) \\ v+a\sin(\phi_A-\theta) \end{pmatrix} \ , \ A_S=\begin{pmatrix} a\cos\phi_A+x_{SE} \\ a\sin\phi_A+x_{SN} \end{pmatrix} \tag{1}$$

in which A and *A'* are the displacement vectors of the expansion joint at the original point A and at the deformed point A', but A_s is a displacement vector of the corresponding ground response at point A. Relative displacement at the expansion joints is calculated by the following formula:

$$\begin{aligned} \boldsymbol{\delta}_{\mathbf{A}} &= \begin{pmatrix} \delta_{1A} \\ \delta_{2A} \end{pmatrix} = \mathbf{Q}_{\mathbf{A}} \begin{pmatrix} x_{SE}-u+a\{\cos\phi_A-\cos(\phi_A-\theta)\} \\ x_{SN}-v+a\{\sin\phi_A-\sin(\phi_A-\theta)\} \end{pmatrix} \\ \mathbf{Q}_{\mathbf{A}} &= \begin{pmatrix} \cos\psi_A & \sin\psi_A \\ -\sin\psi_A & \cos\psi_A \end{pmatrix} \end{aligned} \tag{2}$$

where *a* is the length from the origin (or the gravity center of AOD) of Figure 3.3. to point A, and ϕ_A and ψ_A are angles from the origin and from the bending corner of the concrete structure to point A, respectively.

The structural responses of the two-dimensional displacement and rotational motions are obtained by the following equilibrium equation of motion:

$$\mathbf{M}\ddot{\mathbf{u}}+\mathbf{K}\mathbf{u}=\mathbf{K}\mathbf{x}_{\mathbf{S}} \tag{3}$$

where **M** and **K** are a mass matrix and stiffness matrix, respectively, which are given by

$$\mathbf{M}=\begin{pmatrix} M & 0 & 0 \\ 0 & M & 0 \\ 0 & 0 & I_G \end{pmatrix} \ , \ \mathbf{K}=\begin{pmatrix} k_{E1}+k_{E2} & 0 & (k_{E1}b-k_{E2}c)\sin\phi \\ 0 & k_{N1}+k_{N2} & (k_{N2}c-k_{N1}b)\cos\phi \\ (k_{E1}b-k_{E2}c)\sin\phi & (k_{N2}c-k_{N1}b)\cos\phi & k_{E1}b^2-k_{E2}c^2 \end{pmatrix} \tag{4}$$

and M, I_G are the mass and rotational rigidity of the concrete encased structure, $k_{N1}, k_{N2}, k_{E1}, k_{E2}$ are the spring moduli of the surrounding soil and these spring moduli are evaluated by the Seismic design specification of highway bridges[9], and b, c, ϕ are the length from the center of gravity of A'OD' and structural configuration angle.

The variables **u** and $\mathbf{x}_s$ are the structural response and the free field ground response as given by

$$\mathbf{u}=\begin{pmatrix} u \\ v \\ \theta \end{pmatrix} \ , \ \mathbf{x}_{\mathbf{S}}=\begin{pmatrix} x_{SE} \\ x_{SN} \\ 0 \end{pmatrix} \tag{5}$$

In the numerical analysis, the spring modulus was randomly modified from the original value to smaller ones in order to obtain the largest responses that can exceed the limit boundary of the expansion joint. Figure 3.4. shows the excessive displacements between the ground responses and the structural responses in the axial and transverse directions at points A and D in Figure 3.3. δ_{1A} and δ_{1D} are the responses in the axial direction, and δ_{2A} and δ_{2D} are the responses in the transverse direction, respectively. These figures show that the maximum response appears in the transverse direction of point D, as shown by δ_{2D}. This result does not conflict with the observation that the largest movement at the encased concrete structure occurred at point D in the transverse direction. The second largest response is given by δ_{2A}, which might support the observation that both expansion joints were simultaneously destroyed by the main shock. Figure 3.5. is the rotational response of the concrete encased structure. These structural responses as shown by the triangular and square marks in the multiple limit state diagram for the expansion joint failure modes in Figure 3.6. In this figure, three different performance limit curves are shown as boundary conditions of the joint failure. Here, two modified performance curves were prepared for reduced allowance conditions which correspond to existing settlement before the earthquake. The numerical results suggest that the expansion joints at the site might have produced an existing settlement equivalent to 1/3 to 2/3 of maximum performance before the earthquake.

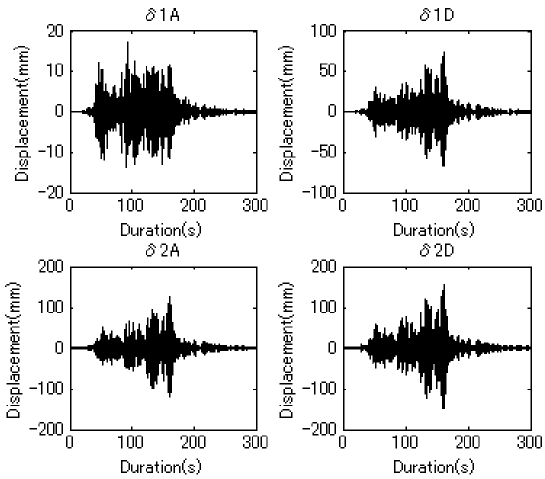


Figure 3.4. Excessive displacement between structural response and ground displacement at expansion joint points A and D, where δ_1 is axial displacement and δ_2 is transverse displacement to the pipe axis

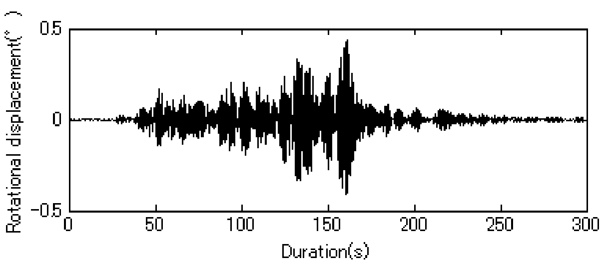


Figure 3.5. Rotational angle of under-crossing concrete encased structure

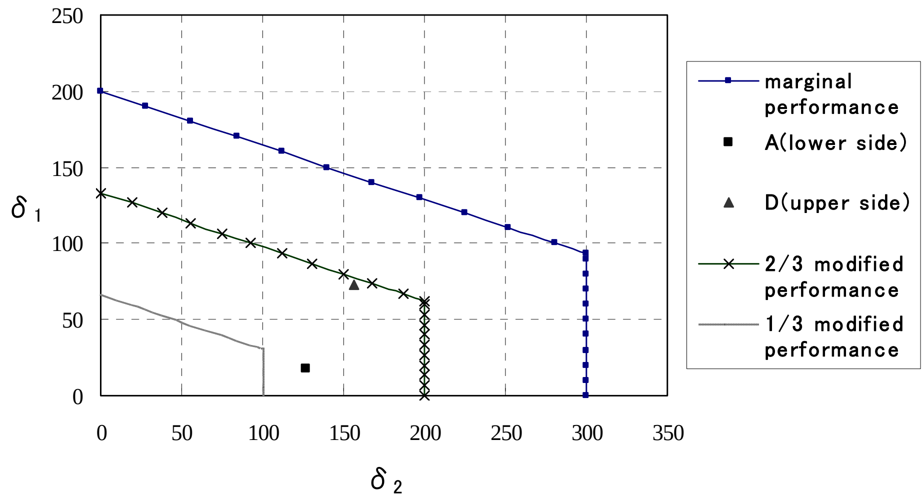


Figure 3.6. Multiple limit state diagram of expansion joint failure modes, in which modified performance curves are generated from the marginal performance curve in deteriorated joint allowance states

3.2. Expansion joint between valve vault and riser system

Leakage failure from an expansion joint occurred in the aftershock of April 7th, approximately one month after the main shock. In this section, the discussion focuses on this one month delay in the accident.

Photo 3.2. shows the damaged expansion joint in which leakage failure occurred at the upper portion of the expansion joint. This expansion joint belongs to closer type, which has housing and rubber ring, as shown in Fig. 3.7. The sealing bolt and ring at the upper portion were hydro-blasted by high pressure water and the half portion was worn out, as shown in Photo 3.3. Fig. 3.8. shows the worn portion and its volume corresponds to 6.3% of the original volume.

From this, the following failure mechanism could be deduced: (1) The main shock of March 11, 2011 produced high pressure water leakage from a small gap in the joint; (2) this water leakage started to wear the metal portion of the sealing parts, and this wear continued for one month; (3) the deteriorated sealing ring could not stop the large scale leakage caused by shaking due to the aftershock of April 7th. In order to confirm this failure scenario, the possibility that these failure steps could occur as a result of the main and aftershocks must be evaluated by the numerical approach.

Photo 3.2. Excavation of joint failure portion

Photo 3.3. Sealing bolt worn out by hydro-blasting

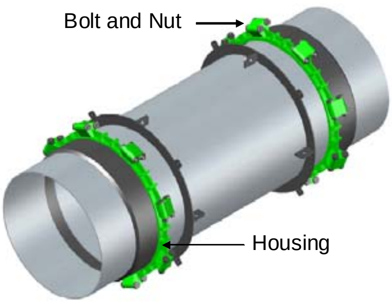


Figure 3.7. Expansion joint structure

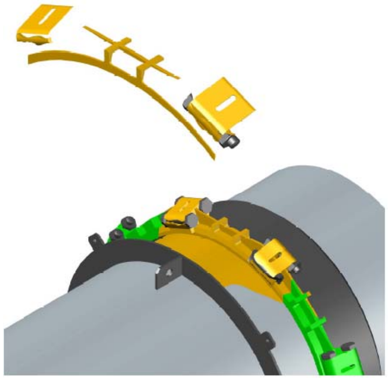


Figure 3.8. Hydro-blasted portion of the expansion joint

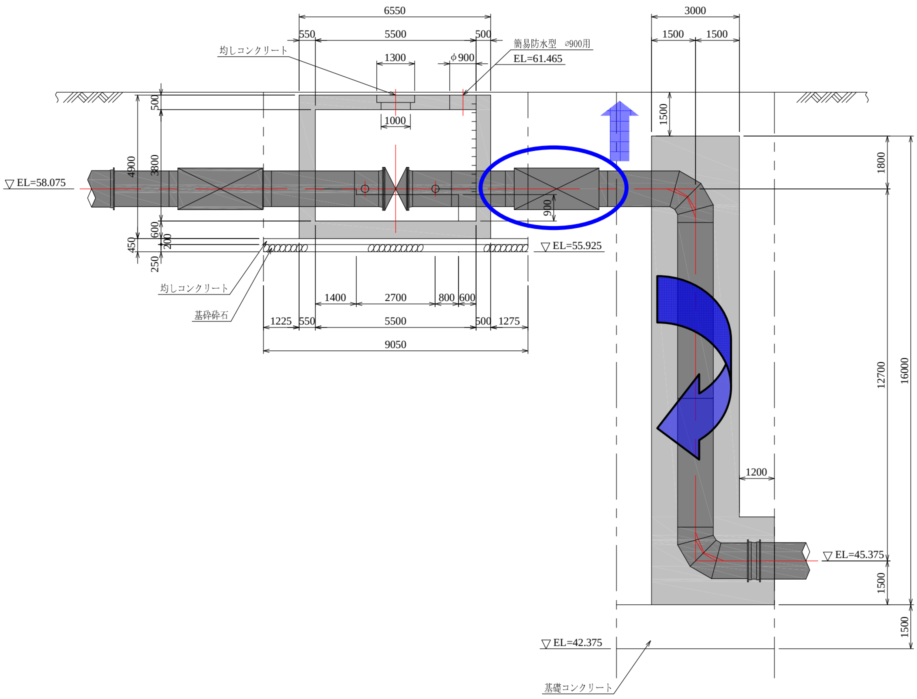
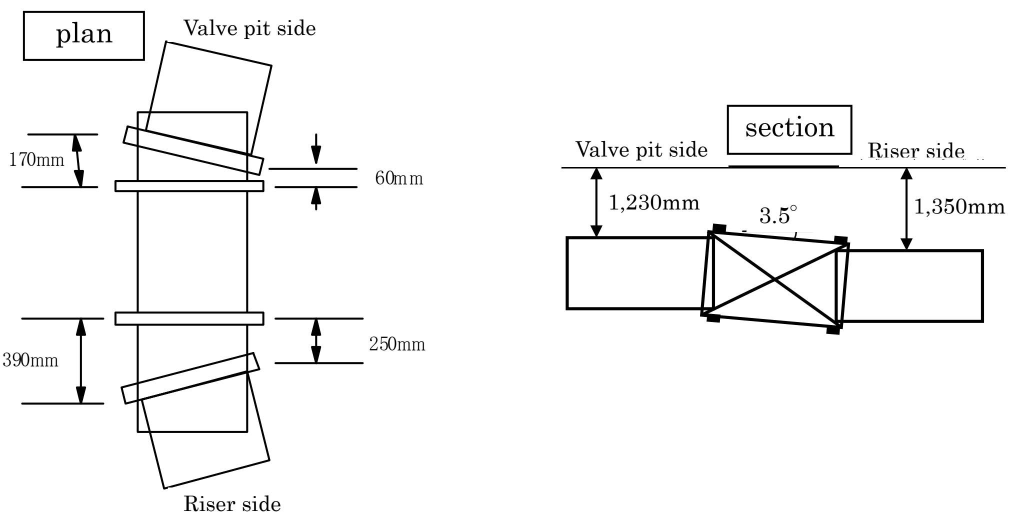


Figure 3.9. Schematic illustration of riser and valve pit system



(a) Plan view (b) Sectional view

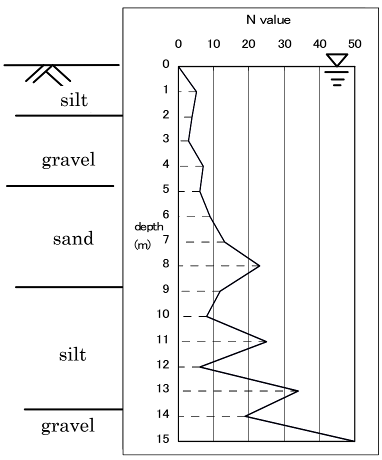
Figure 3.10. Site allocation of expansion joint after leakage

The expansion joint, which is located between the valve pit and the riser structure as shown in Figure 10, had a potential risk of uneven settlement, so that the expansion joint was forced to absorb vertical displacement. As a result of this settlement, the residual allowance for the seismic effect was limited. Based on the site investigation on April 7th, 2011, different vertical settlements were measured at the two ends of the expansion joint, as shown in Figure 3.10. This suggests that the joint had rotated to an angle of 3.5 degree before the earthquake. Using the site soil conditions shown in Figure 3.11., the seismic response of the concrete riser was analyzed with a single-degree-of-freedom system as follows.

$$\begin{pmatrix} -\omega^2 M + \sum k_i & \sum k_i l_i \\ \sum k_i l_i & -\omega^2 I_G + k_R + \sum k_i l_i^2 \end{pmatrix} \begin{pmatrix} x_G \\ \theta \end{pmatrix} = \begin{pmatrix} -M\ddot{x}_Q - \sum k_i (x_Q - x_{si}) \\ \sum k_i x_{si} l_i - x_Q \sum k_i l_i \end{pmatrix} \tag{6}$$

in which x_Q, x_G, x_{si} and θ are base-rock ground motion, structural and surface ground responses, and rotation angle, as shown in Figure 3.12., and, k_i and l_i are the spring constant and the length at the i-th point from the gravity point. I_G and k_R are the rotational rigidity of the riser and its rotational stiffness for the surrounding soil and structural interaction. Figure 3.13. shows the seismic responses of the riser and the expansion joint in the main shock and the aftershock. In the main shock, the maximum rotation is less than 1 degree, which is not sufficient to destroy the expansion joint. This response led to a small leak from the joint since the pre-existing settlement had already produced rotation of 3.5 degree in the expansion joint. According to the fabricator's specification shown in Figure 3.14., the allowable maximum angle is 6 degree, so the main shock could not cause large-scale leakage immediately after the main shock. However, one month after the first small leakage, the hydro-blasting effect had worked on the sealing ring, reducing the thickness of the bolt diameter and the ring itself. As a result, when the second shock occurred in the aftershock of April 7th, the sealing ring had already been worn out, and could easily be broken by a small impact. This is a reason the expansion joint suffered a leakage failure in the aftershock.

In the second example, the pre-existing settlement played an important role in initiating small leakage from the sealing ring, which caused hydro-blasting that reduced the metal portion of the sealing elements. This result suggests that the allowable displacement of the expansion joint should be designed not only for vertical settlement under ordinary construction conditions but also for excessive displacement by future earthquakes.



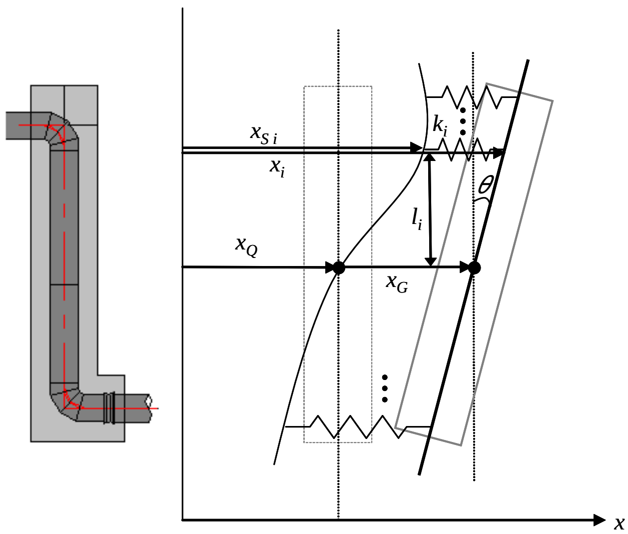


Figure 3.11. Soil classification and N value at site **Figure 3.12.** Configuration of the coordinate system for riser

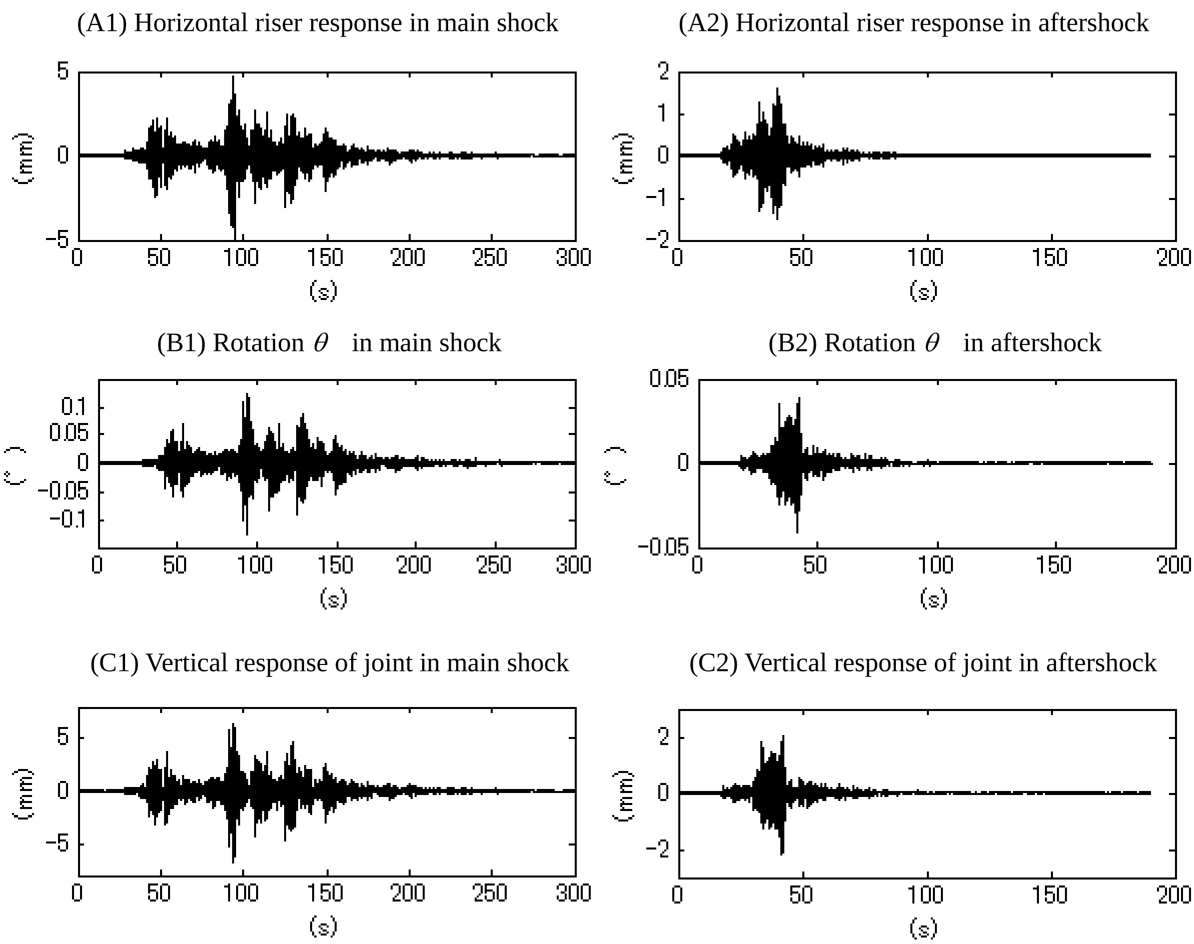


Figure 3.13. Seismic responses of riser and expansion joint in main shock and aftershock

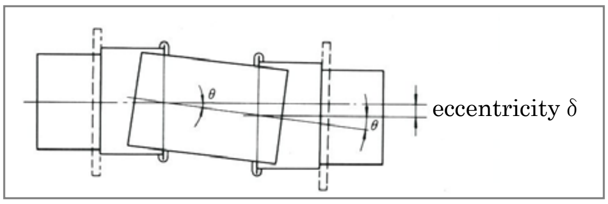


Figure 3.14. Allowable angle of expansion joint for eccentricity δ

4. PROPOSALS FOR SEISMIC DISASTER MITIGATION OF EXPANSION JOINTS

From these two leakage failure events, several points for the improvement of the seismic design method for expansion joints are proposed, as follows:

(1) Asymmetrical shape of a structure can produce unstable responses. Actually, in this example, rotational motion caused simultaneous destruction of the expansion joints. Special attention should be paid to the seismic design of asymmetrical structures.

(2) Generally, one set of expansion joints is installed at the two sides of a valve pit to absorb possible uneven settlement. In this situation, the connected pipes are assumed to be buried in infinite stretches. However, these pipes are often connected to other structures (a riser structure in this case) in the vicinity of the valve pit. Therefore, it should be noted that the expansion joint must not be connected to a pipe which may be subjected to additionally forced settlement.

(3) A routine design for the valve pit and expansion joints should always be assessed based on the total allocation of the structures connected to the pipe from the valve pit.

5. CONCLUSIONS

In the present study, the failure mechanism, which resulted in large-scale leakage from expansion joints of large diameter water pipelines in the 2011 Great East Japan Earthquake is investigated.

One event was triggered by rotation of a concrete encased structure which under-crosses a stream line. The other event occurred approximately one month after the main shock. This delayed failure was attributed to progressive damage of the expansion joint sealing ring by hydro-blasting, which developed from a small initial leak caused by the main shock. These two events were initiated by the seismic responses of the concrete encased structures, in which the one is a spatially developed rigid structure and the other is a vertical rigid structure of a riser.

These examples show that pre-existing settlement and deteriorated performance must be taken into consideration when studying possible failure mechanisms. These results suggest that it is important to maintain an additional displacement allowance for future earthquakes, and to design a symmetrical configuration of the structure which cannot produce unpredicted failure modes.

REFERENCES

Japan Society of Civil Engineers. (2011). Great East Japan Earthquake urgent damage research report, 10-1-10-9.

Sennan, Sen-en wide area water supply office. (2011). Outline of Sennan, Sen-en wide area water supply business (http://www.pref.miyagi.jp/ss-kousui/index.html)

JFE Engineering Corporation. (2011). Great East Japan Earthquake damage of water pipe facilities-Site survey report.

National Research Institute for Earth Science and Disaster Prevention. Kyoshin Network K-net (http://www.k-net.bosai.go.jp/k-net/)

Water Steel Pipe Association. (1997). Expansion joint for water steel pipe, WSP 024-97, WSP.

Yoshida, N. and Suetomi, I. (1999). DYNEQ, (Version 3.01), Sato Kogyo Central Research Institute.

Water Steel Pipe Association. (2011). Damage analysis of water pipe in Great East Japan Earthquake and suggestion for recovery.

Water Steel Pipe Association. (1979). Water pipe facilities earthquake-proof method of construction guideline and explanation, 1979 version.

Japan Road Association. (2002). Seismic design specification of highway bridges.