Seismic Performance Analysis of the Transmission Gas Pipeline in the 2011 Great East Japan Earthquake

S. Mori & K. Chiba
Japan Petroleum Exploration Co., LTD., Tokyo, Japan

T. Koike
Kyoto University, Kyoto, Japan

SUMMARY:
A seismic safety assessment for the transmission pipeline affected by ground failures after the 2011 Great East Japan Earthquake is developed. The seismic performance of the surviving pipeline is estimated considering the survival condition. Discussion is also devoted to the pipeline integrity in terms of the probability of failure.

Keywords: Seismic performance analysis, transmission gas pipeline, pipeline integrity assessment

1. INTRODUCTION

Seismic effects and the tsunami produced by the 9.0-M_w Great East Japan Earthquake on March 11, 2011 caused significant damages to human resources and materials in many areas of the East Pacific region in Japan.

The high-pressure transmission gas pipeline[1)] owned by Japan Petroleum Exploration Co., Ltd. (JAPEX) crosses Japan from the Sea of Japan to the Pacific Ocean. The eastern half of the pipeline and its related facilities such as valve stations, SCADA system, and dispatch offices were affected by the ground motions and the tsunami, and several facilities located in the coastal area were severely damaged by the tsunami. However, the transmission pipeline itself did not incur any damages and maintained its integrity even at the sites that suffered permanent ground deformations, which occurred in mountain areas. Bcause the pipeline and its relevant facilities were rapidly restored, the gas supply to the distribution network in the city of Sendai was successfully restarted two weeks after the earthquake.

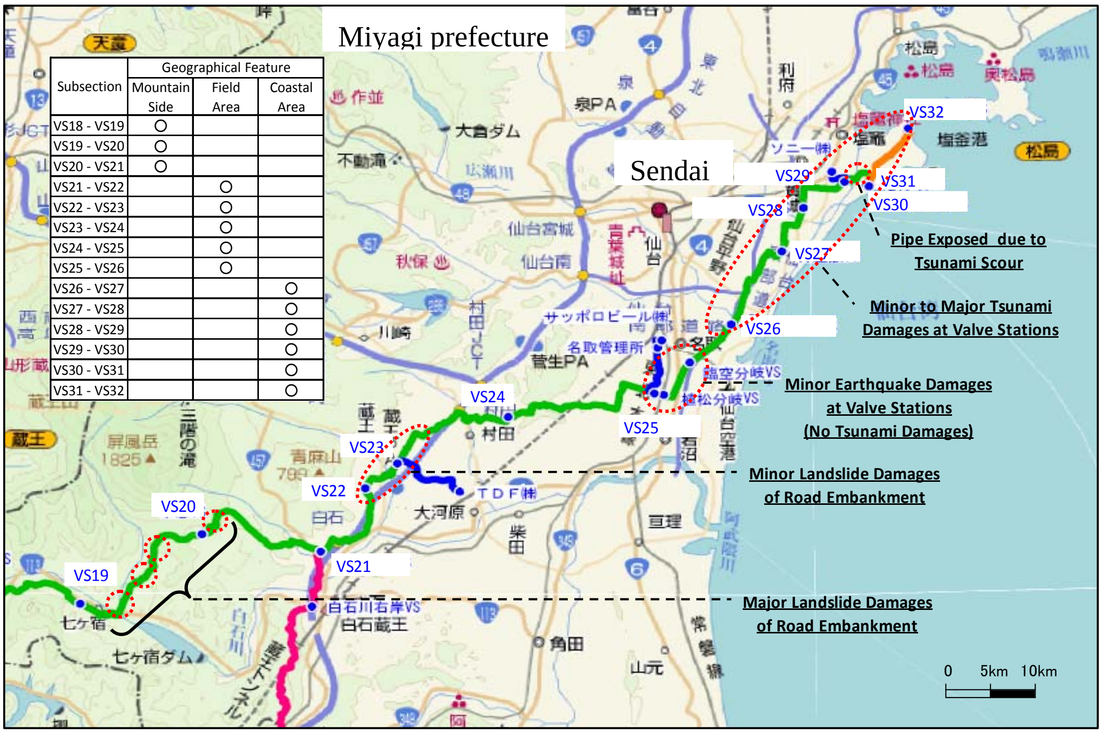
The seismic design standards for high-pressure transmission gas pipelines, which were revised based on the seismic damage observations of past earthquakes, require a high safety performance with regard to the materials and equipment of current high-pressure transmission gas pipeline systems. Unfortunately, no events have occurred to verify the seismic safety of these pipelines, especially against extremely large earthquakes. The 2011 Great East Japan Earthquake is the first case in Japan where the transmission pipeline’s highly qualified seismic performance against significantly large earthquakes was verified.

In the present study, discussions are devoted to the following topics: (1) a seismic safety assessment of the transmission pipeline affected by the ground failures in the mountain areas and (2) a seismic risk analysis of the pipeline integrity[4),10)] for the rapid restoration and immediate re-operation.

2. SEISMIC DAMAGES IN THE 2011 GREAT EAST JAPAN EARTHQUAKE

2.1. Pipeline route

Figure 1 shows the route map of the pipeline, which comprises 14 subsections with valve stations at both ends. The total length of the pipeline in the eastern half is approximately 112.7km, of which the western three subsections are on the mountain side, the subsequent five subsections pass through the field area, and the remaining sections are in the coastal area. The terminal base is located at the new Sendai port area in the vicinity of the city of Sendai.



Subsection	Mountain Side	Field Area	Coastal Area
VS18 - VS19	○		
VS19 - VS20	○		
VS20 - VS21	○		
VS21 - VS22		○	
VS22 - VS23		○	
VS23 - VS24		○	
VS24 - VS25		○	
VS25 - VS26		○	
VS26 - VS27			○
VS27 - VS28			○
VS28 - VS29			○
VS29 - VS30			○
VS30 - VS31			○
VS31 - VS32			○

Figure 1. Pipeline route map

2.2. Damages of the terminal facilities

Figure 2 shows the terminal facilities submerged by the tsunami of March 11, 2011. Almost all the pipelines in this section were exposed to and submerged under the sea because of liquefaction and tsunami erosion effects, over 1km. A pig-inspection was conducted after the earthquake to assess the pipeline integrity with regard to air tightness and cross-sectional deformation, although some portions of the pipeline had damage caused to the external coating, which was burned by a tank fire disaster, or were mechanically damaged slightly by debris attacks.

Figure 2. Terminal facilities submerged by the tsunami of March 11, 2011

2.3. Damages along the coastal areas

While the valve station VS26 along the coastal area was not significantly damaged, the valve stations VS27 to VS32, which are located at river crossings, suffered damage to warehouses and electrical instrumentation owing to floating objects or debris during the tsunami. For example, Figure 3 shows the Google map of valve station VS27 before and after the tsunami, in which the fence and warehouse incurred minor damages and the foundation of the exhausting tower was settled, while the transmission pipeline itself maintained its integrity.

(1) Before the tsunami (2) After the tsunami

Figure 3. Valve station and exhausting tower before and after the tsunami

2.4. Damages in the mountain areas

In the mountain areas of valve stations VS 18 to VS23, significant damages occurred to the road body. Especially notable was the subsection of VS19 to VS20, which incurred major landslide damages of the road embankment at three sites as shown in Figure 4. The pipeline was exposed along some portions, and the pipeline moved with the soil displacement along other portions. Although these severe geotechnical damages occurred[3)], the pipeline did not exhibit any significant damages.

Based on the site survey of the pipe locations affected by the landslide per each link between the valve stations, the occurrence rate was approximately 0.0058 /km $(\approx 6/1000km)$.

After the earthquake, the site survey was conducted to assess the collapse of the embankment and the settlement of the road surface or landslide. The vertical settlement and horizontal displacement from the road surface were measured at the damage points shown in Figure 4. The pipe settlement profile was analyzed with regression curves for the wide span and for the narrow span, as shown in Figure 5. The maximum bending strain of 0.0026 was detected in model 2 as shown in Table 1.

Figure 4. Ground failures and deformed pipelines

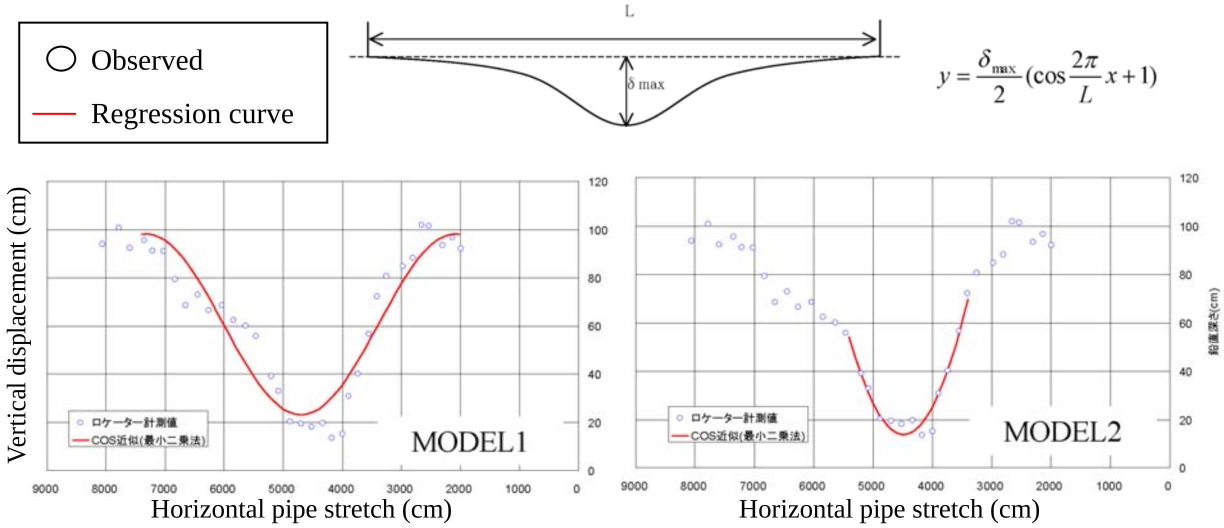


Figure 5. Pipe strain distribution to predicted by pipe linear alignment measured by pipe locator

Table 1 Measured pipe strains

Model	Length (m)	displacement (cm)	Maximum bending strain
model 1	53	76	0.0014
model 2	20	21	0.0026

Table 2 Pipe dimensions and characteristic values

Item	Symbol	Unit	Value
Diameter	D	mm	508
Thickness	t	mm	11.91
Min. stress	σ_y	MPa	422
Design factor	C		0.4
Pressure	P_r	MPa	7

3. SEISMIC PERFORMANCE OF THE ORIGINAL PIPELINE

3.1. Original pipe design

Generally, the pipe-wall thickness of a high-pressure gas pipeline is determined by the internal pressure condition. Actually, the pipe wall thickness of the JAPEX pipeline was designed such that the hoop stress, σ_{hoop}, in Eq.1 was less than the allowable stress, $C\sigma_y$, in Table 2.

$$\sigma_{hoop} = \frac{P_r(D-t)}{2t} = 1458kgf/cm^2 = 146MPa \tag{1}$$

where P_r, D, and t are the internal pressure, diameter and pipe-wall thickness, respectively.

3.2. Former seismic design

3.2.1 Former design earthquake

In Japan, the seismic design method for oil pipelines was based on the Petroleum Pipeline Design Standard, which was established in 1974, in which the seismic load is given in terms of a design velocity spectrum at the base rock. This was the first seismic design formula of buried pipelines, which is called “the response displacement method.” This design approach adopted the allowable stress criterion to evaluate the pipeline design parameters. This elastic design approach is effective for comparatively small earthquakes, but it is not appropriate for severely large earthquakes to produce the inelastic response. Therefore, after the 1995 Kobe Earthquake, two types of design earthquake concepts[6)] were introduced in terms of Level 1 ground motion (EQ1) and Level 2 ground motion (EQ2). The former ground motion corresponds to an earthquake for the serviceability limit state or the maximum operational earthquake. The latter is for the ultimate limit state or the maximum considerable earthquake.

Figure 6 shows the design velocity spectra of seismic design guidelines for various pipelines such as JAPEX, Japan Road Association (JRA), and Japan Gas Association (JGA)[5)]. In this figure, A,B, and C indicate the soil type of the ground along the JAPEX pipeline, and JRA-EQ1 and JGA-EQ1 are design spectra for Level 1 seismic ground motion of the JRA and JGA seismic design guidelines, respectively, and JGA-EQ2 is a design spectrum for Level 2 seismic ground motion.

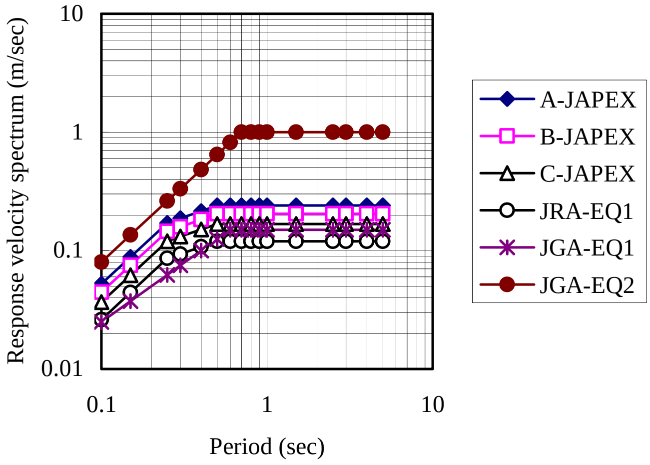


Figure 6. Design velocity spectra of buried pipelines in Japan

3.2.2 Seismic design method before the 1995 Kobe Earthquake

The former seismic design method[1] for Level 1 ground motion can be formulated as follows:

(1) Design criterion: $\sigma_S \le \sigma_{cr}$ (2)

(2) Combined stress: $\sigma_S = \sqrt{3.12\sigma_L^2 + \sigma_B^2}$ (3)

where Axial stress: $\sigma_L = \alpha_1 E \varepsilon_G$, Bending stress: $\sigma_B = \dfrac{2\pi D}{L} E \alpha_2 \varepsilon_G$ (4a)

Ground strain: $\varepsilon_G = \dfrac{\pi}{L} U_h$, Displacement: $U_h = \dfrac{2}{\pi^2} S_V(T) \cdot T \cdot \cos\left(\dfrac{\pi}{2H} z\right)$ (4b)

$$\alpha_1 = \frac{1}{1 + \left(\dfrac{\sqrt{2}\pi}{\lambda_1 L}\right)^2}, \quad \alpha_2 = \frac{1}{1 + \left(\dfrac{2\pi}{\lambda_2 L}\right)^4}, \quad \lambda_1 = \sqrt{\frac{K_1}{EA}}, \quad \lambda_2 = \sqrt[4]{\frac{K_2}{EI}} \quad (4c)$$

where $\sigma_{cr}, L, E, T, H, S_V, K_1, K_2, A, I, z$ are the yield stress; wave length; Young's modulus; typical period of the surface ground; thickness of the surface ground; design response velocity spectrum; spring moduli for the axial and transverse directions, respectively; the cross sectional area; and rigidity of the pipe; cover of depth; respectively. However, this design method does not include any assessment for permanent ground displacement.

3.2.3 Seismic design method after the 1995 Kobe Earthquake

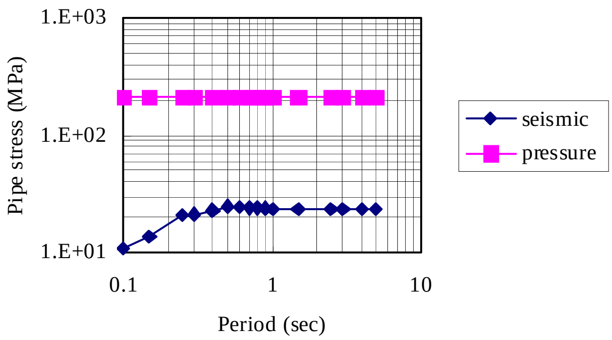
Based on the significant damages caused to the pipelines during the 1995 Kobe Earthquake, almost all the seismic design guidelines were revised, and thus, the guideline[5] for the buried pipelines was formulated for two types of seismic loads, Level 1 and Level 2 ground motion. The former design formula defined in Equations 1 to 4 was used for the Level 1ground motion, and a revised formula was introduced for Level 2 ground motion and is as follows:

(1) Design criterion: $\varepsilon_S \le \varepsilon_{cr}$ (5)

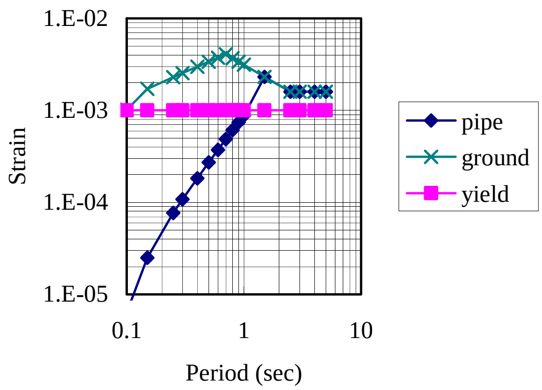
(2) Strains: $\varepsilon_S = q\alpha_1 E \varepsilon_G$, $\varepsilon_G = \dfrac{2\pi}{L} U_h$ (6)

where ε_{cr} is the critical axial strain[11] for the seismic load of EQ2, with the critical strain level in the inelastic range of 1% to 3% for ground shaking and 3% to 5% for permanent ground displacement in the revised JGA (JGA-EQ2), and q is a factor for estimating the slippage effect at the pipe surface for the seismic load of EQ2.

In Figure 7(1), two pipe stresses are compared, where the stress due to the internal pressure is significantly higher than that due to the seismic load (EQ1). In Figure 7 (2), on the other hand, the seismic pipe strain due to EQ2 does not exceed the yield level for periods less than 1.5 s. These numerical results suggest that a pipeline designed based on internal pressure is strong enough for the seismic loads of EQ1 and EQ2 if the pipe exhibits a sufficient elongation performance with a high-quality welded joint. From this point of view, the JAPEX pipeline was strong enough for the 2011 Great East Japan Earthquake, although the pipeline was originally designed for the seismic load of EQ1, and the effect due to the seismic load of EQ2 was not considered for the construction that occurred before the 1995 Kobe earthquake.



(1) Hoop stress for internal pressure and combined stress for seismic load (EQ1) of buried gas pipelines



(2) Axial strains of ground and pipe for seismic load (EQ2) compared with the yield strain of buried gas pipelines

Figure 7. Pipe stresses and strains for seismic loads of EQ1 and EQ2 compared with internal pressure and ground motion

4. SEISMIC RISK ASSESSMENT OF THE SURVIVING PIPELINE

4.1. Failure probability of the original pipeline

The original pipeline was designed based on the allowable design approach, in which the safety factor was the critical design parameter for determining the pipe wall thickness. The safety factor was established to consider any possible allowances in the uncertain load and strength. By assuming that these allowances are the confidence intervals with $k_s V_S$ and $k_R V_R$ (V_X: coefficient of variation of a random variable X and k_X: a constant for the confidence interval), the probability of failure corresponding to the safety factor can be calculated as follows.
The central safety factor, λ_0, for the design variables of R and S can be represented by the coefficient of variation, V, and the reliability index, β, as follows[9]:

$$\lambda_0 = \frac{1+\beta\sqrt{V_R^2 + V_S^2 - \beta^2 V_R^2 V_S^2}}{1-\beta^2 V_R^2} \tag{7}$$

Once the central safety factor is determined, the corresponding reliability index can be obtained by Eq.8. When the random variables are described by normal distributions, the probability of failure is given by

$$p_f = \Phi(-\beta) \tag{8}$$

For the case in which $k_R = 0.05, k_S = 0.05, V_R = 0.05, V_S = 0.25$, the relationships among the safety factor, the reliability index, and the probability of failure are shown in Figure 8. In this figure, the central safety factor of 2.0 corresponds to a reliability index of 3.75 and a probability of failure of 8.84×10^{-5}.

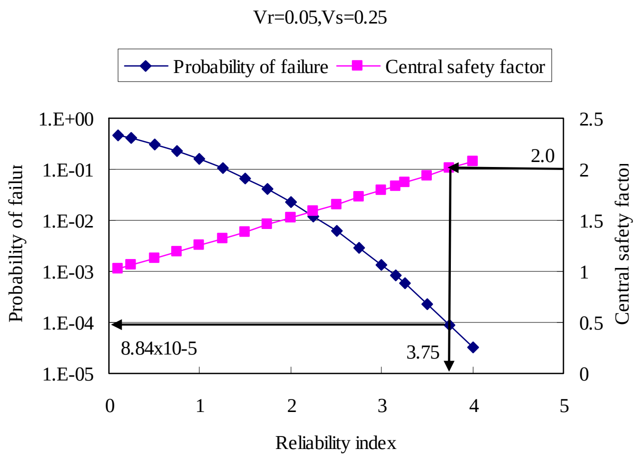


Figure 8. Mutual relationship among the reliability measures

Because a pipeline is a stretched structure, structural failure will occur at any potential defects randomly distributed along a pipeline route which covers a mountain side, field area, or coastal or reclamation area. Pipe failures are caused by the defects introduced by third parties (external interference), corrosion, construction activities, or ground movement. The general statistics on these failure events are summarized in Table 3. From this table, the failure frequencies per causes are 0.01 to 0.17 per 1000 km.year.

Table 3 Failure frequencies per cause[2)]

Cause	Failure frequency in 1970-2011 per 1000km.yr
External interference	0.17
Corrosion	0.057
Construction defect/Material failure	0.059
Hot tap made by error	0.017
Ground movement	0.026

This rate will increase because of the deteriorating effect of the surrounding conditions of a pipeline, or will decrease because of frequent patrols, periodic inspections and repair activities. The following function[8)] is introduced to take this effect into consideration.

$$g(t) = \left(1 + b \cdot \frac{t}{T_d}\right)^a \tag{9}$$

where T_d is a service period, and a and b are control parameters. In this study, the values of a and b were simply assumed to be 2 and 0.5, respectively, in order to evaluate the deteriorating effect.
If the original pipeline was designed with a central safety factor of 2.0 or a corresponding failure probability of 8.84×10^{-5}, the probability of failure of the original pipeline is estimated with a Poisson process assumption of a random defect occurrence as

$$P[D_{pr}] = 1 - \exp[-L \cdot T_v \cdot v_0 g(t) P(C \cdot \sigma_y \le \sigma_{hoop})] = 1 - \exp(-112.7/1000 \times 1 \times 0.1 \times 8.84 \times 10^{-5}) = 9.95 \times 10^{-7} \tag{10}$$

where L, T_v, and v_0 are the length of the pipeline, the time interval assumed to be 1, and the occurrence rate of the potential defects assumed to be 0.1, respectively, and $g(t)$=1.0 for t=0.

4.2. Failure probability of the pipeline under the revised seismic condition after the 1995 Kobe Earthquake

After the 1995 Kobe earthquake, the new seismic load of EQ2 was given in terms of two sets of velocity spectra; a 90% non-exceeding curve and a 70% non-exceeding curve. These two curves were obtained from the regression analysis of many velocity response spectra obtained at various sites during the 1995 Kobe earthquake. By using these two curves, the mean value and its coefficient of variation of the designed response spectrum are obtained with the log-normal assumption as follows;

$$E\left[\ln S_V^{EQ2}\right] = \ln S_V^{90} / \left\{1 + \mathrm{cov}\left(\ln S_V^{EQ2}\right) \cdot \Phi^{-1}(0.9)\right\}, \qquad E\left[\ln S_V^{EQ2}\right] = \ln S_V^{70} / \left\{1 + \mathrm{cov}\left(\ln S_V^{EQ2}\right) \cdot \Phi^{-1}(0.7)\right\} \tag{11}$$

With this velocity spectrum of S_V^{EQ2}, the probability of pipe failure at a potential defect is obtained by the following equation:

$$P\left[D_{shake}\right] = P\left[\varepsilon_{cr}^{shake} \le \varepsilon_p^{EQ2}\right] = \Phi\left[-\frac{\mu_{\ln Z_s}}{\sigma_{\ln Z_s}}\right] \tag{12}$$

where ε_{cr}^{shake} is the critical pipe strain for the ground shaking due to the seismic load of EQ2 and the remaining variables are defined by the following equations:

$$\varepsilon_p^{EQ2} = q\alpha_1 \cdot \frac{2\pi}{L} \cdot \frac{2}{\pi^2} S_V^{EQ2}(T) \cdot T \tag{13}$$

and

$$\mu_{\ln Z_s} = E\left[\ln Z_s\right] = E\left[\ln \varepsilon_{cr}^{shake} - \ln \varepsilon_G^{EQ2}\right], \sigma_{\ln Z_s} = \sqrt{\sigma^2_{\ln \varepsilon_{cr}^{shake}} + \sigma^2_{\ln \varepsilon_G^{EQ2}}} \tag{14}$$

In a similar manner, the probability of failure for permanent ground displacement (PGD) can be determined as

$$P\left[D_{PGD}\right] = P\left[\varepsilon_{cr}^{PGD} \le \varepsilon_{PGD}\right] = \Phi\left[-\frac{\mu_{\ln Z_d}}{\sigma_{\ln Z_d}}\right] \tag{15}$$

where ε_{cr}^{PGD} and ε_{PGD} are the critical strain and the pipe strain produced by PGD, respectively, and the remaining variables are defined by the following equations:

$$\mu_{\ln Z_d} = E\left[\ln Z_d\right] = E\left[\ln \varepsilon_{cr}^{PGD} - \ln \varepsilon_{PGD}\right], \sigma_{\ln Z_d} = \sqrt{\sigma^2_{\ln \varepsilon_{cr}^{PGD}} + \sigma^2_{\ln \varepsilon_{PGD}}} \tag{16}$$

The seismic damages can be assumed to initiate from these defect points. The probability of failure for the pipeline system is calculated with a Poisson process assumption of a random defect occurrence as

$$P\left[D_{EQ}^{shake}\right] = 1 - \exp\left[-LT_v \nu_0^{shake} g(t) P\left(D_{shake}\right)\right], \qquad P\left[D_{EQ}^{PGD}\right] = 1 - \exp\left[-L\nu_0^{PGD} g(t) P\left(D_{PGD}\right)\right] \tag{17}$$

where ν_0^{shake} and ν_0^{PGD} are the occurrence rates of the potential defects for ground shaking and permanent ground displacement, respectively.

4.3. Seismic risk assessment of the pipeline immediately after the 2011 Great East Japan Earthquake

4.3.1. Revision of the pipeline parameters under the survival conditions

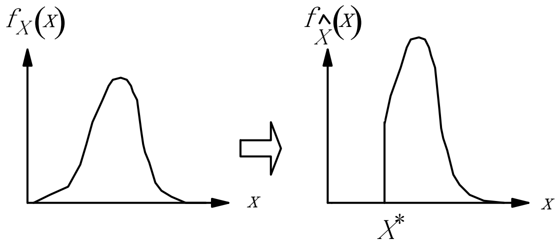
Based on the fact that the pipeline survived the 2011 Great East Japan Earthquake, the design parameters assumed to be random variables were revised in their probability distributions such that the seismic response was a result of the proof load test in the real situation, as shown in Figure 9. The conditional probabilities for Eqs.12 and 15 are then iven by

$$P\left[D_{shake} \middle| EQ_2^*\right] = P\left[\varepsilon_{cr}^{shake} \le \varepsilon_G^{EQ2} \middle| \varepsilon_G^{EQ2*} < \varepsilon_{cr}^{shake}\right] \tag{18}$$

$$P\left[D_{PGD} \middle| EQ_2^*\right] = P\left[\varepsilon_{cr}^{PGD} \le \varepsilon_{PGD} \middle| \varepsilon_{PGD*} < \varepsilon_{cr}^{PGD}\right] \tag{19}$$

where ε_G^{EQ2*} and ε_{PGD*} are the ground strain and PGD along the pipeline which were measured or estimated for the 2011 Great East Japan Earthquake.

Based on the site observation, large ground displacements were found on the mountain side, but in the field and coastal zones, liquefaction settlement or lateral spreading could not be identified because the tsunami attacked the coastal area. Therefore, in this analysis, the occurrence rate of PGD for liquefaction was roughly assumed to be 2 - 5 /1000 km based on past observations[5)] of liquefaction occurrences. Table 4 shows the occurrence rate of potential defects per $1000 km \cdot yr$ for cracking, ground shaking, and PGD.



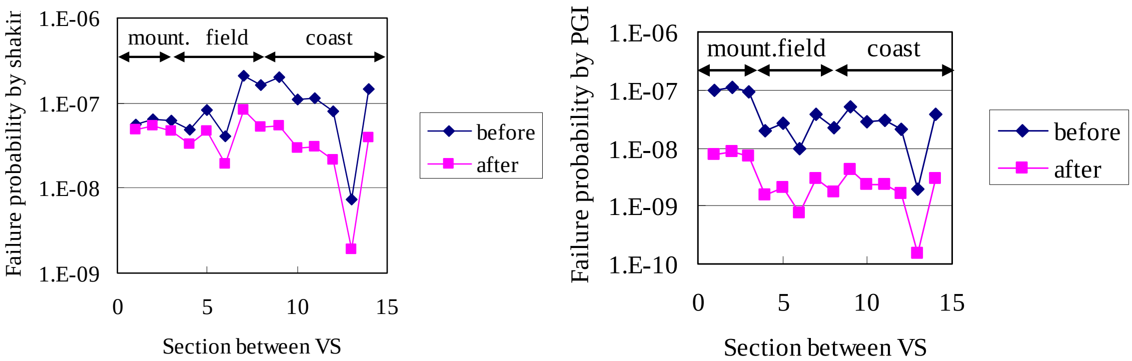
(1) Before the earthquake (2) After the earthquake

Figure 9. Probability density function revised to consider the fact that the system survived for known load X*

In Figure 10, the failure probabilities of the pipe sections between valve stations due to ground shaking and PGD before and after the 2011 Great East Japan Earthquake are compared. The curve representing the assessment after the 2011 earthquake (red poly-lines) is significantly different from that before the earthquake for the probability of failure due to PGD. The original failure probability due to PGD is replaced by the revised probabilities at all site conditions.

Table 4 Occurrence rate of potential defects per 1000 km.yr

Occurrence rate	ν_0^{crack} (per 1000km.yr)	ν_0^{shake} (per 1000km.yr)	ν_0^{PGD} (per 1000km)		
	Site classification				
	general	general	liquefaction	fault	landslide
before 1995	0.1	0.1	2~5	0	6
1995〜2011	0.1	0.1	2~5	0	6
after 2011	0.1	0.1	The critical value is revised with the observed data		



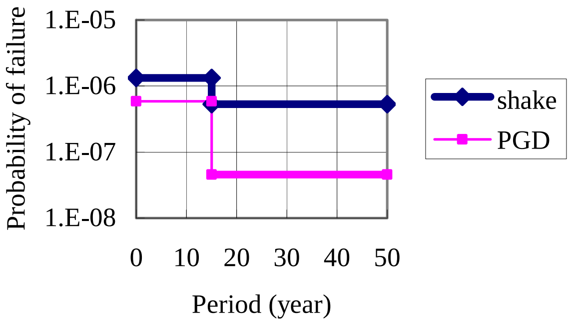
(1) Ground shaking (2) Permanent ground displacement (PGD)

Figure 10. Failure probability of pipe sections before and after the 2011 Great East Japan Earthquake

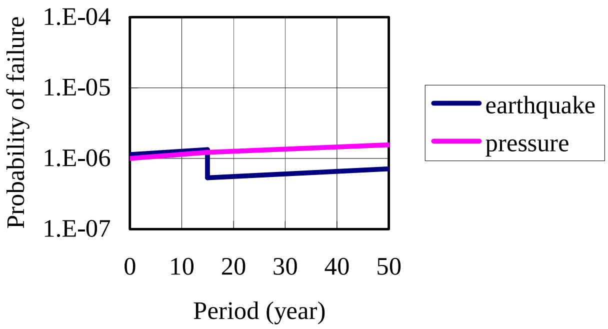
4.3.2 Seismic risk assessment of pipeline integrity affected by the survival conditions

Figure 11(1) shows the failure probability of the pipeline before and after the 2011 earthquake. The abrupt change at the 15th year, representing the 2011 earthquake event can be derived from Eq.17 which reflects the fact that the pipeline integrity was maintained.

In Figure 11 (2), the failure probability due to the seismic effect of Level 2 ground motion is slightly improved compared with that due to the internal pressure after the 2011 earthquake.



(1) Failure probability of pipeline for ground shaking and PGD before and after the 2011 earthquake.



(2) Failure probability of pipeline for ground shaking under deteriorating circumference conditions before and after the 2011 earthquake.

Figure 11. Failure probability of pipeline before and after the 2011 Great East Japan earthquake

5. CONCLUSIONS

1) A seismic safety assessment method was developed to demonstrate the resilience of the pipeline integrity survived after the 2011 earthquake based on actual site observations along the high-pressure gas transmission pipeline.
2) The failure probabilities of the original and surviving pipelines evaluated for Level 2 ground motions will be useful for investigating the risk estimation and seismic investment for the maintenance management of the pipeline.
3) Frequent monitoring of potentially hazardous locations not only in the mountain route but also in the coastal zone is recommended. Terminal facilities located in the coastal area must be protected from tsunami hazards and liquefaction hazards.

REFERENCES

1) Egawa, T., Sugai, H. and Murase T. (1995). Technology of steel structure in Niigata-Sendai gas pipeline project, Journal of Steel Structures, Vol.2, No.8, pp.13-27.
2) EGIG (2011). Gas pipeline incidents, 8th Report of the European Gas Pipeline Incident Data Group, Document Number EGIG 11.R.0402 (version 2).
3) Honegger, D.G., Hart, J.D., Phillipe, R., Popelar, C. and Gailing, R.W. (2010). Recent PRCI guidelines for pipelines exposed to landslide and ground subsidence hazards, Proceedings of the 8th International Conference IPC2010, Canada.
4) Hopkins, P. (2002). The structural integrity of oil and gas transmission pipelines, Comprehensive structural integrity, Vol.1, Elsevier Publishers.
5) Japan Gas Association (2000). Seismic design guideline for high pressure gas transmission pipelines, JGA.
6) Japan Road Association (1974). Technical guideline for petroleum pipelines, Japan Road Association.
7) Johnson, E.R., Metz, M.C. and Hackney, D.A. (2003). Assessment of the below-ground trans-Alaska pipeline following the magnitude 7.9 Denali fault earthquake, 6th Congress and Workshop on Lifeline Earthquake Engineering, TCLEE, ASCE.
8) Koike, T. (2005). Maintenance strategies of pipelines by risk management approach, JSCE No.794/I-72, pp.189-202.
9) Melchers, R.E. (1999). Structural Reliability Analysis and Prediction Second Edition, WILEY.
10) Porter, M. and Esford, F. (2004). Estimating the influence of natural hazards on pipeline risk and system reliability, IPC04-0238, Proceedings of IPC 2004 International Pipeline Conference, Canada.
11) Suzuki, N., Igi, S. and Masamura, K. (2008). Seismic integrity of high-strength pipelines, JFE Technical report, No.12, pp.14-19.