Seismic Design of High Pressure Gas Pipeline Applying "HIPERTM"[†]

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Abstract:

Goal-setting design has been introduced into the seismic design of high pressure gas pipelines since 2001 in Japan. Requirements for the design concept to ensure pipeline integrity to withstand small and medium earthquakes shall be securing normal operability, which means no damage shall occur and operation immediately after an earthquake can be resumed. As for large and huge earthquakes and permanent ground deformation such as lateral spreading and surface faults, pressure integrity shall be taken into account to prevent leakage of pipeline containment. This paper explains examples of strain-based design applying "HIPER TM " for the lateral spreading and fault movement defining the critical local buckling strain as allowable strain. The results show that JFE's "HIPERTM" will be effective to ensure pipeline integrity compared to conventional pipes. The API 5L line pipe with L450 (X65) grade (API: The American Petroleum Institute), outside diameter of 609.6 mm, was used for the case studies.

1. Introduction

Following the 1995 Great Hanshin-Awaji (Kobe) earthquake, long distance, high pressure gas pipelines have been designed in consideration of ground response due to large earthquakes and permanent ground deformation (lateral spreading) in order to further enhance their seismic resistance.

As the present practice in seismic design for pipelines^{1, 2)}, goal-setting design preconditioned on securing integrity (pressure integrity) is performed for lateral spreading.

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*1 Group Manager, Construction Dept., Electric Power, Oil & Gas Engineering Div., JFE Engineering In the history of design standards, as outlined in **Table 1**, goal-setting design on the responsibility of the pipeline operator or gas company is assumed for items in connection with seismic safety other than the study items which are now required, such as whether or not to reuse a pipeline in which pressure integrity is secured (i.e., no leakage of the pipeline containment as a result of deformation) after deformation or fault displacement involving larger deformation than that described above, etc.

This paper presents the basic concept of goal-setting design of pipelines and examples of seismic design using JFE's high strain linepipe "HIPERTM."

2. Seismic Design Standards for High Pressure Gas Pipelines

2.1 Seismic Design in Accordance with Gas Business Act

The laws applicable to high pressure gas pipelines in Japan are the "Gas Business Act," "Electricity Business Act," "High Pressure Gas Safety Act," and "Mine Safety Act." This paper presents the basic concept of seismic design standards under the Gas Business Act, which provides standards beginning with seismic design for ground motion and also including liquefaction-induced permanent ground deformation.

In the Gas Business Act, the "Ministerial Ordinance Establishing the Technical Standards of the Gas Facilities" of 2000 stipulated goal-setting design, and preconditioned securing safety under the responsibility of the gas operator. However, the general method is design in



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	Year	Design codes	Checking items	Critical parameters for design	
	1974	Petroleum Pipeline Design Codes (Draft) ³⁾	Ground motion	Allowable stress	
	1995	(The 1995 Kobe Earthquake)			
	2000	Seismic Design Codes for High Pressure Pipelines	Ground motion Level-2	Allowable strain	
2001		Seismic Design Guidelines Considering Lateral Spreading	Lateral spreading ground settlement	Allowable bending angle	
	2011 (The 2011 Tohoku Offshore Earthquake)				
	2012 and after	Company's own design codes	Large deformation fault movement	Specific parameters	

Table 1 History of seismic design codes

Table 2 Allowable strain and allowable deformation of high-pressure gas pipelines

Ground displac	cement	Deformation mode Seismic integ		Allowable strain
Temporary ground deformation	Ground motion Level-1	Cyclic axial deformation (<i>N</i> =50)	Normal operability	Straight: 1% or 35 <i>t</i> / <i>D</i> Bend: 1%
	Ground motion Level-2	Cyclic axial deformation (<i>N</i> =3–5)		Straight: 3% Bend: 3%
Permanent ground deformation	Lateral spreading	Bending deformation (Irreversible)	Pressure integrity	Straight: 30% Bend: Opening: 10% Closing: 30%

accordance with "Design Examples Based on the Technical Standards of the Gas Facilities"⁴⁾ for basic items and allowable strain-based design in accordance with the "Seismic Design Code for High Pressure Gas Pipelines"¹⁾ and "Seismic Design Guidelines Considering Liquefaction-induced Lateral Spreading"²⁾ for seismic design.

2.2 Concept and Issues in Setting Allowable Values

The allowable values in seismic design standards differ depending on the study item. This is because the magnitude and frequency of loads applied to pipelines differ depending on the respective study items.

(1) Stress-Based Design (Elastic Design)

The allowable value of the primary load is defined as the yield point (σ_y) divided by the safety factor: 2, and the allowable values of other secondary loads are set by multiplying various increment factors, depending on frequency and other considerations.

(2) Strain-Based Design (Nonlinear Design)

As shown in **Table 2**, the value of allowable strain is set considering the deformation mode of the various types of displacement that occur in earthquakes, frequency, and other factors.

Among the above methods, the concept for the allowable value of deformation for Ground Motion Level-2 and higher affecting gas pipelines is "Pressure integrity" (no leakage of pipeline containment). "Normal operability" of the pipeline after deformation is not assumed.



Fig. 1 Ground deformation and corresponding

Furthermore, as shown in **Fig. 1**, in addition to the existing criteria, fault displacement is classified as large ground deformation. Because pipelines are linear structures, the possibility that a pipeline may cross a fault cannot be ruled out, and in such cases, goal-setting design for fault displacement is also necessary in order to secure a higher level of seismic safety in the pipeline.

3. Examples of Goal-Setting Seismic Design

3.1 Linepipe with Excellent Deformation Performance: "HIPERTM"

Conventionally, deformation performance had been expressed as a function of the pipe wall-thickness and pipe diameter as shown in Eq. (1). Therefore, in order to improve deformation capacity, it was necessary to increase the thickness of the pipe wall^{5, 6)}.

D: Pipe diameter, t: Pipe wall-thickness

In contrast, Eq. (2) expresses deformation performance as a function of the strain-hardening characteristics of the material, which means that deformation capacity can be improved by improving the strainhardening properties of the material without increasing pipe wall-thickness. In "HIPERTM," deformation performance has been improved by improving the properties.

$$\varepsilon_{\rm pcr} = \frac{4}{3} \sqrt{n} \left(\frac{t}{D}\right) - \frac{\sigma_0}{2\rm E} (1+n) \dots (2)$$

E: Young's modulus,

n: Strain-hardening exponent, σ_0 : Yield stress

3.2 Comparison of Critical Compressive Strain

The following sections present examples of design using a simplified analysis method and the allowable values for liquefaction-induced lateral spreading and fault displacement, when using pipes of the 3 specifications shown in **Table 3**.

The allowable value of the criterion for design is critical local buckling strain, based on seismic integrity securing "Normal operability" (i.e., no damage shall occur, and it shall be possible to resume operation without repairs immediately after an earthquake).

Critical local buckling strain is generally obtained by finite element analysis (FEA) using shell elements. **Table 4** shows the allowable value (ε_{cr}) that was set based on FEA using shell elements.

The allowable value is the 2D average critical compressive strain (ε_{cr}) at initiation of local buckling as the center⁷). The local buckling characteristics of straight pipes were determined in advance by shell element anal-

Table 3	Pipe	dimensions	used for	finite	element	analysis
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Parameters	Conv. (1)	Conv. (2)	"HIPER""	
Pipe grade	API 5L L450 (65)			
Pipe diameter (mm)	609.6			
Wall thickness (mm)	14.3	20.6	14.3	
Yield ratio	0.93	0.85		
Stress ratio, $\sigma_{2.0}/\sigma_{1.0}$	1.01	1.03		

Table 4 Critical compressive strain for the pipelines

	Conv. (1)	Conv. (2)	"HIPER""
Critical compressive strain, $\varepsilon_{\rm cr}$	0.87%	1.06%	1.46%







(2) Conv. (2) presents the distribution at peak moment



ysis, and a deformation analysis of the pipelines, which were modeled as beam elements, was performed by setting ε_{cr} .

Figure 2 (1)–(3) show the longitudinal strain distribution of the 3 types of pipe when the respective pipes reached critical local buckling strain. It can be understood that local concentration of strain is slight in "HIP-ERTM" in comparison with the conventional pipe, Conv. (1) and Conv. (2), because "HIPERTM" has excellent tensile properties.

3.3 Example of Bending Deformation Induced by Lateral Spreading

This section presents an example of verification of the seismic characteristics of the 3 pipes discussed in this paper against liquefaction-induced lateral spreading.

Figure 3 shows the analytical model. The pipe is modeled as a beam element, and the soil spring in the



Fig. 3 Analytical model of a pipeline across a lateral spreading zone



Fig. 4 Maximum longitudinal compressive strain

"Seismic Design Guidelines Considering Liquefaction-Induced Lateral Spreading" is used for the ground.

Figure 4 shows the results of spreading up to a maximum displacement of 5 m in lateral spreading, assuming lateral spreading breadths W = 20, 40, 60, and 80 m. From these analytical results, the deformation modes of



Fig. 5 Comparison of pipeline integrity in the lateral spreading zone

the pipelines differ greatly depending on the breadth of lateral spreading and the magnitude of ground displacement. With both Conv. (1) and Conv. (2), ground displacement was 2–3 m when the lateral spread breadth was 40 m and was on the order of 4.5 m at W = 60 m. Under these conditions, both of the conventional pipes reached ε_{cr} and local buckling began.

Because the allowable values of these 3 pipes were different, the strain generated in each pipe was converted to a non-dimensional value by ε_{cr} and compared as shown in **Fig. 5**. Under the analytical conditions for lateral spreading used in the present analysis, both Conv. (2), which has a pipe wall-thickness specification 1.44 times thicker than that of Conv. (1), and Conv. (1) exceeded ε_{cr} at 40 m and 60 m. From this, it can be understood that the only pipe that can be applied under these conditions is "HIPERTM," which has the same wall-thickness as Conv. (1).

3.4 Example of Bending Deformation Induced by Fault Displacement

This section presents an example of verification of the seismic properties of the 3 pipes against fault displacement.

For fault displacement, an analysis of the deformation of the 3 pipes was performed assuming the pipelines crossing a strike-slip fault like that shown in **Fig. 6**. As in Section 3.3, the pipelines were modeled as beam elements and spring elements were used for the ground, but in this case, the spring characteristics provided in the "Seismic Design Code for High Pressure Gas Pipeline" were used.



Fig. 6 Analytical model of a pipeline crossing a fault line



Fig. 7 Maximum longitudinal compressive strain of the three pipelines

The analytical results are shown in Fig. 7.

The fault displacement at which the pipes reached the allowable value was 1.75 m for Conv. (1), 2.62 m for Conv. (2), and 4.60 m for "HIPERTM." From these results, "HIPERTM" can be used in locations when fault displacement is 4 m or less, and "HIPERTM" and Conv. (2) can be used when fault displacement is no more than 3 m.

Thus, assuming the same material standard, higher seismic performance can be secured without increasing the pipe wall-thickness by applying "HIPERTM".

4. Conclusion

Because greater consideration will be given to the seismic integrity of pipelines in the future, it is considered that strain-based design will become increasingly important. This paper has shown that further improvement in seismic integrity is possible in strain-based design by adopting a design method that considers the properties of the material, etc., rather than simply setting an allowable value based on the yield point, as has been the practice until now.

This paper presented allowable values suitable for various deformation modes, proposed a simple analytical design method accompanying them, and gave examples of analyses using 3 types of pipes of the same standard.

Because pipeline operators will be required to carry out separate goal-setting design and improve seismic performance in the future, an examples of an analysis in which seismic integrity was improved by considering material properties without increasing pipe wallthickness, as with "HIPERTM", was also presented.

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