Seismic Design Guidelines To Mitigate Upheaval Buckling Of Small Diameter Pipes

Hajime Shinkai
Japan Gas Association, Tokyo, Japan

Yoshito Hatsuda
Tokyo Gas Company, Ltd., Tokyo, Japan

Nobuhisa Suzuki
JFE Techno-Research Corporation, Kawasaki, Japan

ABSTRACT
This paper describes The Draft Seismic Design Guidelines to Mitigate Upheaval Buckling of Small Diameter Pipes which were reported by Ministry of Economy, Trade and Industry in 2011. The upheaval buckling was occurred due to strong ground motion during the 2007 Niigata-ken Chuetsu-oki earthquake which was a powerful moment magnitude 6.6 earthquake. A three year research program had been conducted since 2008 to investigate upheaval buckling behaviors and develop seismic design guidelines to ensure seismic integrity of small diameter pipelines.

1.INTRODUCTION

The three year research program aimed to solve the following three key issues. The first issue aimed to develop an appropriate finite element model to predict the critical axial strain at the onset of upheaval buckling and simulate the following post buckling behaviors including local buckling. The second issue required validation of finite element analysis (FEA), the FE model and their results, conducting sand box tests and field tests using 4” pipes. And the third issue requested to develop a proper methodology for seismic diagnosis and countermeasures useful to mitigate upheaval buckling induced by seismic waves.
The governing parameters of upheaval buckling behavior are recognized as pipe diameter, wall thickness, material tensile properties, length of straight line, and pipe-soil interaction. In order to validate the FE model, a series of laboratory and field tests of upheaval buckling of 4” pipe was conducted. Validation of FEA was made comparing the test data and the FEA results. The test pipes were idealized by fine mesh, four-node shell elements over the entire length which is the same element as that used for the local model.
The critical values are significantly dependent on material hardening properties. For instance, while the onset strain of upheaval buckling of a 4” pipe with Luders Elongation (LE) type stress-strain curve is predicted as 0.31%, that with Round-House (RH) type s-s curve is estimated to be 2.29% which is 7.4 times as large as the previous one. After the three year research program, METI drafted Seismic Design Guidelines to Mitigate Upheaval Buckling of Small Diameter Pipes, where strong seismic excitation had been taken into account.

The upheaval buckling of 4” high-pressure gas pipeline is presented in Figure 1. which occurred during the 2007 Chuetsu Offshore earthquake. A sand box test set-up for upheaval buckling and a buckled pipe after test are shown in Figure 2. The general configurations and the wave length of the buckled portion in Figure 2 present very good agreement with those of the actual post-buckling deformation observed in Figure 1. In-field upheaval buckling tests were also conducted however the details are not introduced here for the lack of space.
The Seismic Design Guidelines to Mitigate Upheaval Buckling of Small Diameter Pipes has been drafted after the three year research program. The Draft Guidelines consists of the following five chapters and the details are described below using the corresponding chapter numbers.

- GENERAL RULES
- BASIC CONCEPT OF SEISMIC DESIGN
- SEISMIC DESIGN PROCEDURES
- HOW TO METIGATE UPHEAVCAL BUCKLING
- DESCRIPTION OF SEISMIC DESIGN TO METIGATE UPHEAVAL BUCKLING

Figure 1. Upheaval buckling of 4” pipe

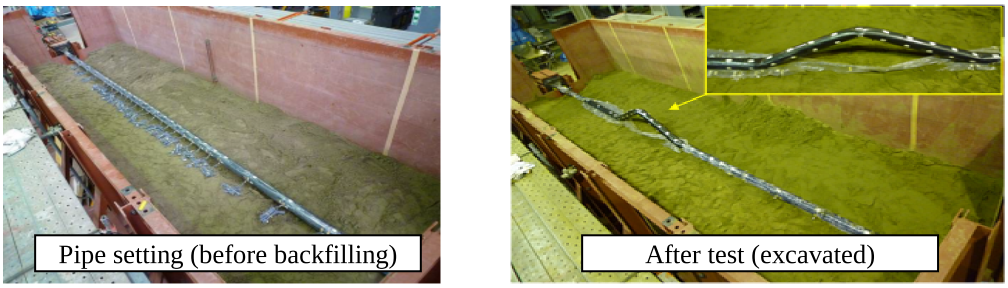


Figure 2. Laboratory test of upheaval buckling

2. GENERAL RULES

2.1 Purpose

These guidelines deal with seismic mitigation with respect to upheaval buckling of small diameter high-pressure pipelines and middle-pressure main distribution lines induced by strong ground shaking. The following remarks should be noted:

(1) The 2007 Chuetsu Offshore earthquake caused the upheaval buckling of a small diameter high-pressure pipeline and middle-pressure main lines, whose diameters were 4” and smaller, at 15 locations due to strong ground shaking. Following the 2007 earthquake, the Committee on City Gas Utilities and Facilities Investigating the Effect of the 2007 Chuetsu Offshore earthquake (the Committee) was held, which was chaired by Dr. Tsuneo Katayama, Professor at Tokyo Denki University. The Committee proposed to establish Seismic Design Guidelines for Small Diameter Pipes to withstand Upheaval Buckling (the Guidelines) which takes into account strong ground shaking.

(2) This document describes the draft Guidelines which is an outcome of the Research Project on Seismic Mitigation of Gas Pipelines which was conducted from 2008 to 2010.

2.2 Scope of application

The guidelines are applicable to 4” and smaller diameter high-pressure pipelines and significant middle-pressure lines which are planning to be constructed. The following remarks should be noted:

(1) The 2007 Chuetsu Offshore earthquake caused the upheaval buckling of 4” high-pressure pipelines at two locations. For the middle-pressure lines the following were impacted for each size of pipe; 4” three locations, 3” - five locations and 2” locations. However, no upheaval buckling was reported after the 1995 Hyogo-ken Nambu earthquake (the Kobe earthquake). Furthermore, upheaval buckling of pipes with diameters of 6” and larger was not reported for the same gas distribution areas. Hence the Committee concluded that the small diameter pipes of 4”

and less may be highly susceptible to upheaval buckling deformation. Thus, the guidelines should be applied to high-pressure pipelines and middle-pressure main lines with diameters of 4” and less.

(2) Although mitigations or countermeasures should be taken for high-pressure pipelines and middle-pressure main lines, it should be noted that gas companies may have their own interpretation of what constitutes main lines. For example, in some cases, the definition for the main line can be described as follows. The middle-pressure main lines would have a significant role during restoration efforts after an earthquake. The main line also means a supply line to disaster response bases and steam power plants.

2.3 Definitions of terms

The major terms used in the guidelines are defined as follows. (Other terms have been defined in the JGA Guideline 2006-03.)

(1) Upheaval buckling

Upheaval buckling means beam-mode buckling of buried pipes whose wave length can be determined in terms of pipe bending rigidity and surrounding soil spring properties. The buckled pipe tends to deform upward during the post-beam-buckling deformation and subsequent local buckling in bending may be observed. Consequently the local buckling may result in pipe break and leakage of containments.

(2) Onset strain of upheaval buckling

Onset strain of upheaval buckling corresponds to critical longitudinal pipe strain where longitudinal compressive pipe stress reaches its maximum.

(3) Onset strain of local buckling

Onset strain of local buckling, which is defined during the post-upheaval buckling deformation, expresses the critical longitudinal pipe strain due to bending and bending moment reaches its maximum at the corresponding pipe section.

(4) Length of straight line

This is the distance between two weld lines of a straight pipe that is connected to a bend with a bending angle of 22.5 degrees or more at both ends. In the guidelines, the main pipe of the tee-junction is regarded as straight pipe, and the branch is regarded as a 90-degree bend.

The following remarks should be noted:

(1) The upheaval buckling deformation process is presented in Figure 3.

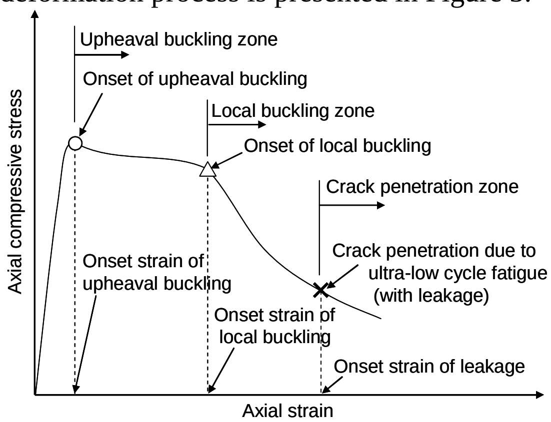
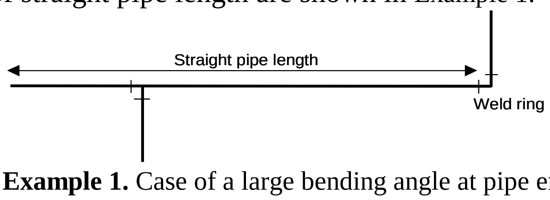


Figure 3. Upheaval buckling deformation

(2) Conceptual examples of straight pipe length are shown in Example 1.



Example 1. Case of a large bending angle at pipe end

3. BASIC CONCEPT OF SEISMIC DESIGN

(1) Ground Motion Level-2 (GML-2) should be considered in the seismic design which is defined in the JGA Guidelines 2006-03.
(2) Pressure integrity should be ensured for the gas pipes (No leakage allowing large deformation)
(3) If upheaval buckling might occur due to the assumed Level of Ground Motion and if the strain generated in the pipe due to subsequent deformation might exceed the allowable strain, an upper limit for the straight pipe length of the gas pipe should be provided to achieve a seismic design that satisfies the required seismic capacity.
(4) Items that are not defined in this guideline should comply with the JGA Guidelines 2006-03.

The following remarks should be noted:
(1) The design ground motion and the seismic integrity required for gas pipes should be the same as those of GML-2 defined in the JGA Guidelines 2006-03.
(2) According to experiments using 4” pipes to study upheaval buckling, when an axial compression is applied to a pipe, the pipe begins to bend upward (initiation of upheaval buckling) at the point where the axial compression reaches its maximum. Subsequently, pipe deformation due to upheaval buckling progresses, and local buckling then begins (onset of local buckling) at the point where the bending moment reaches its maximum. In the experiments, a pipe was deformed to the extent where axial strain easily exceeded the onset strain of local-buckling; however, any through-wall crack was not found in the pipe. Accordingly, it has been verified that for the longitudinal displacement (only compression), the critical deformation is located beyond the onset of local buckling. Test results show very good agreement with the FEA results obtained using the local FE model .

According to the result of FEA with respect to axial displacement (only compression) by using the local finite element model, axial strain at the onset of local-buckling is 2D average compressive strain[*1] which is within the range of 6 to 9%. However, when cyclic loading due to seismic waves shall be taken into consideration, it is difficult to determine the critical stage of the pipe at a location beyond the local-buckling start point. Therefore, to be conservative, allowable strain is determined to be 3% in the same manner as the seismic design for GML-2 defined in the JGA Guidelines 2006-03. Thus, seismic integrity which is equivalent to that of the conventional guideline for seismic design of high-pressure gas pipes can be ensured.

[*1] The average value of the axial compressive strain of the compression side (the side toward the center of curvature of the bent pipe) in the section of 2D length (two times of outside diameter) with the buckled portion at the center.

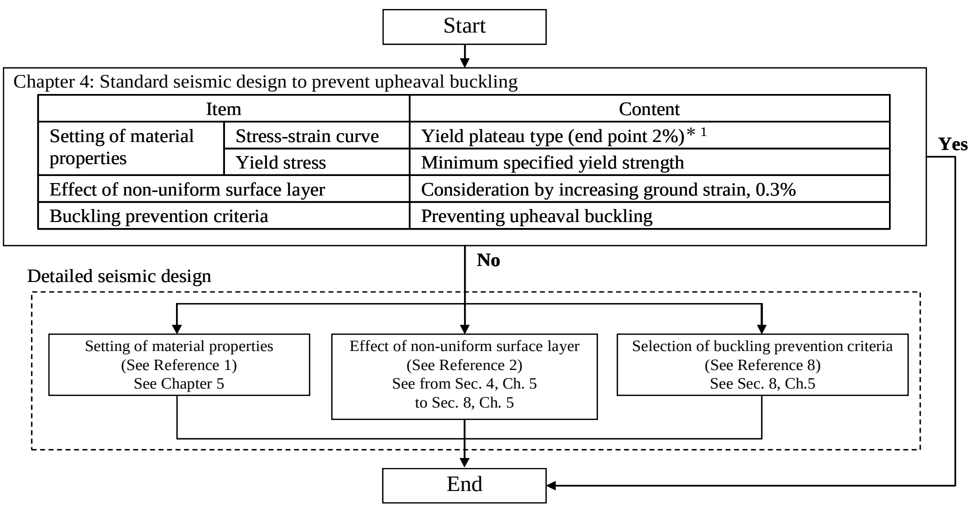


Figure 4. Seismic design procedure to prevent upheaval buckling
*1) Stress-strain curve has a clear yield plateau with 2% Luder's elongation

(3) When the length of straight line is long enough, the axial compressive force generated by seismic waves becomes large which may initiate upheaval buckling. On the contrary, when the length of straight line becomes short, it becomes insufficient to occur upheaval buckling. Therefore, if strain which might occur in the pipe exceeded the allowable strain, the basic principle for seismic design to prevent upheaval buckling is to set an upper limit for the straight pipe length.

4. SEISMIC DESIGN PROCEDURES

Seismic design should be conducted in accordance with Chapter 4, "Standard seismic design to prevent upheaval buckling." When conducting a detailed evaluation of the seismic design, refer to Chapter 5, "Detailed seismic design to prevent upheaval buckling" and necessary materials of this guideline.

The following remark should be noted:
(1) The seismic design procedure in this guideline is shown in Figure 4.

5. HOW TO METIGATE UPHEAVAL BUCKLING

The following seismic design should be conducted according to the natural ground period:
(1) When a natural ground period is within the range shown in Table 1, the length of straight line should be equal to or less than that presented in Table 2.
(2) When a natural ground period is short or long compared to the range shown in Table 1, the straight pipe can be any length.
(3) When the natural ground period is not surveyed, the length of straight line should be equal to or less than the value shown in Table 2.

The following remarks should be noted:
(1) The standard seismic design procedure is shown in Figure 5.

Table 1. Natural period of the ground for which seismic design is necessary

Pipe type	Nominal diameter	Natural period of ground (s)	
		Uniform surface layer	Non-uniform surface layer
SGP	2”	0.7 – 1.8	0.7 or more
	3”	0.8 – 1.1	0.8 – 2.0
	4”	0.8 – 0.9	0.8 – 1.4
STPG370	4”	0.9 – 1.0	0.9 – 1.8

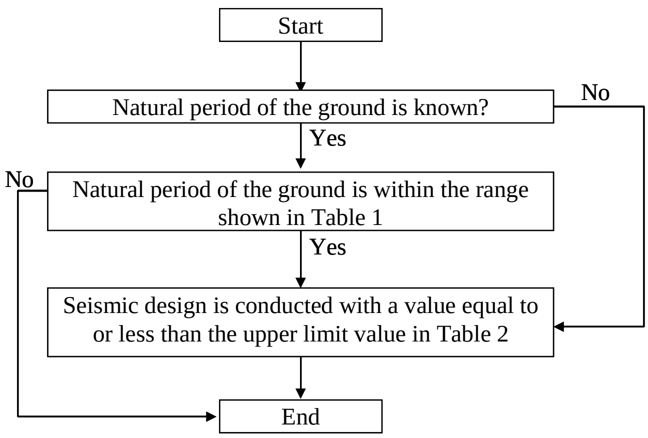


Figure 5. Standard seismic design procedures

(2) "Uniform surface layer" means that the subsurface ground has an almost uniform thickness. "Non-uniform surface layer" means that the subsurface ground has inclined thickness where the longitudinal ground strain tends to concentrate within the shallow portion.

Table 2. Upper limit of straight pipe length

Pipe type	Nominal diameter	Bending angle at the straight pipe end				Remarks
		90 deg.	45 deg.	22.5 deg.	Less than 22.5 deg.	
SGP	2"	82m	63m	30m	Regarded as a straight pipe and added to the connected straight pipe and evaluated.	When bending angles of bent pipes at both ends are different, an average value of the two bent pipes is calculated.
	3"	92m	71m	34m		
	4"	99m	77m	37m		
STPG370	4"	162m	125m	60m		

Table 3. Conditions for standard seismic design

Item	Content	Remarks
Pipe type	SGP, STPG370sch40	
Tensile properties	Yield plateau type (end point 2%)	See Reference 1.
Yield stress	Minimum specified yield strength	SGP is 3/5 of tensile strength.
Earth covering	1.5 m	
Critical strain of upheaval buckling	Calculated using partial analysis model	See Reference 6.
Design seismic motion	Design seismic motion I	See JGA Guidelines 2006-03
Ground spring in direction perpendicular to longitudinal axis	Hyperbolic approximation	See JGA Guidelines 2006-03

(3) When the external force of an earthquake equivalent to the GML-2 (assumed by the JGA Guidelines 2006-03) acted on the long straight 4" or less gas pipes, which were buried in the ground having a natural period within the range shown in Table 1 under the conditions shown in Table 3, upheaval buckling began and the strain generated by subsequent pipe deformation caused the allowable strain of 3% to be exceeded. Therefore, when the natural period of the ground is within the range shown in Table 1, seismic design should be conducted by setting an upper limit for the length of the straight pipe.

(4) In Table 1, axial pipe strain is calculated assuming the length of straight line to be infinite; however, as the length of straight line is gradually decreased, strain generated due to deformation after the onset strain of upheaval buckling becomes equal to the allowable strain of 3%. If the straight pipe is not longer than this length, local buckling will not begin. Furthermore, as the length of the straight pipe is further decreased, the generated strain becomes equal to the onset strain of upheaval buckling and the length of straight line becomes equal to the length at which upheaval buckling occurs. If this length is not reached, upheaval buckling will not occur. There are no differences in the upper limits of the lengths of straight line at which either local buckling or upheaval buckling does not occur. Therefore, to be conservative, we adopted the upper limit value of the straight pipe length at which upheaval buckling does not begin . In Table 2, the upper limit value of the straight pipe length is rounded down to the nearest integer. Accordingly, for seismic design, the straight pipe length should be equal to or less than the applicable value. Herein, the straight pipe length is the distance between two weld lines of a straight pipe that is connected to a bend having a bending angle of 22.5 degrees or more. In this guideline, the main of tee is regarded as a straight pipe, and a branch is regarded as a 90-degree bend.

(5) The upper limits of the straight length were compared between two situations: one in which a bent pipe was connected to the end of the straight pipe and the other in which a loop was connected to the end of the straight pipe. The result was that the straight pipe length was slightly shorter when a bent pipe was connected. Therefore, in Table 2, to be conservative, the upper limit value of the straight pipe length in the former case was adopted .

(6) When the upper limits of the straight length were compared between the uniform ground and the non-uniform ground, the straight length was slightly shorter in the non-uniform ground. Therefore, in Table 2, to be conservative, the upper limit value of the straight pipe length in the latter case was adopted .
(7) A bend with a bending angle of less than 22.5 degrees has little influence on the upper limit value of the straight pipe length. Therefore, such a pipe is regarded as a straight pipe, and the length of the pipe is added to the length of the subsequent straight pipe and evaluated.
(8) The natural ground period should be calculated in accordance with Section 5.2.1, "Natural ground period" in the JGA Guidelines 2006-03.
(9) Table 3, which shows conditions for calculating Table 1 and Table 2, has been established to be conservative. Detailed seismic design can be based on Chapter 5, "Detailed seismic design to prevent upheaval buckling."
(10) Compacting the ground around pipes is effective for mitigating upheaval buckling because it can ensure an initial gradient of the ground confining force in the direction perpendicular to the pipe's axis, which has a great effect on upheaval buckling start strain .

6. DESCRIPTION OF SEISMIC DESIGN TO METIGATE UPHEAVAL BUCKLING

6.1 Material characteristics of gas pipes

6.1.1 Yield stress
The minimum yield point of the specifications should be used for the yield stress.

The following remarks should be noted
(1) For a material such as SGP for which a minimum yield point is not prescribed in the specifications, the yield stress should be 60% of the tensile strength as prescribed by the Japanese Industrial Standards (JIS) according to Appendix 4 of the Announcement of the Gas Business Act.
(2) If the yield stress of the material to be used is known, it can be used.

6.1.2 Tensile characteristics
Tensile characteristics should be set properly according to the material to be used.

The following remarks should be noted
(1) Tensile characteristics have a significant effect on upheaval buckling start strain. Generally, materials having yield plateau type (end point 2%) tensile characteristics tend to have a small upheaval buckling start strain, and materials having Round House type tensile properties tend to have a large upheaval buckling start strain. Since tensile characteristics are not prescribed by specifications, they are unknown unless individual tensile tests are conducted.
Accordingly, when tensile characteristics are unknown, to be conservative, seismic design should be conducted by assuming that the material has yield plateau type (end point 2%) tensile characteristics. In a material having round house type tensile characteristics, upheaval buckling start strain is sufficiently large; therefore, strain occurring in a pipe due to level-2 seismic motion will not reach the upheaval buckling start strain .
(2) If the tensile characteristics of the material to be used are known, they can be used.

6.2 Design seismic motion

Design seismic motion should be set in accordance with Section 5.1, "Design seismic motion" in the JGA Guidelines 2006-03.

6.3 Subsurface ground displacement and ground strain

Surface ground displacement and ground strain should be obtained in accordance with Section 4.2, "Surface ground displacement and ground strain" in the JGA Guidelines 2006-03.

6.4 Non-uniform ground

Non-uniform ground may induce large ground strain compared that induced in uniform ground. Therefore, seismic design should be conducted in accordance with Section 5.3, "Non-uniform ground" in the JGA Guidelines 2006-03.

The following remarks should be noted.

(1) There are various ways of converting ground strain that occurs in non-uniform ground into a ground displacement distribution, such as a method in which the seismic wavelength is fixed and maximum ground displacement is increased, and a method in which the seismic wavelength is reduced and maximum ground displacement is fixed. Strain in a gas pipe is greater with the former method, so this method, in which the seismic wavelength is fixed and maximum ground displacement is increased, should be adopted to conduct a conservative evaluation .

(2) It is also possible to evaluate in detail the strain that occurs in non-uniform ground by a two-dimensional earthquake response analysis using shear waves.

6.5 Pipe-soil interaction

Pipe-soil interactions in the longitudinal and transverse directions should be used to simulate upheaval buckling and local buckling behaviors and expressed by hyperbolic functions whose maximum values are defined with those values described in Sections 4.4.1 and 4.4.2 of the JGA Guidelines 2006-03.

The following remarks should be noted

(1) The onset strain of upheaval buckling is strongly dependent on the initial tangent of the transversal pipe-soil interaction. Therefore the onset strain of upheaval buckling tends to increase with increasing initial tangent. The longitudinal and transversal pipe-soil interactions described in the JGA Guidelines 2006-03 are expressed with bilinear functions and the initial tangents are small compared to the test data. Hence the pipe-soil interactions in the Guidelines should be presented with hyperbolic functions determining the initial tangents with the test data and their maximum values with those values calculated in accordance with the JGA Guidelines 2006-03.

(2) Test data with respect to the pipe-soil interactions can be used instead of the above mentioned description.

6.6 Onset strain of upheaval buckling

Onset strain of upheaval buckling should be analyzed by finite element analysis using the partial model.

The following remarks should be noted

(1) The onset strain of upheaval buckling can be obtained using the partial model that involves a 15-meter center portion. It has been confirmed that the analysis results using the partial is model properly coincide with the test results. The global model for finite element analysis has a length of entire seismic wavelength however its post-upheaval buckling behavior is unstable and very difficult to simulate converge.

(2) If the calculations converge by the use of the global model, it is possible to use the global model to estimate the onset strain of upheaval buckling.

6.7 Onset of buckling

6.7.1 Onset of upheaval buckling

A comparison should be made between the pipe strain obtained according to Section 5.5, "Seismic design of straight pipes" in the JGA Guidelines 2006-03 and the onset strain of upheaval buckling obtained in accordance with Section 5.6, "Onset strain of upheaval buckling."

(1) When the pipe strain is equal to or greater than the onset strain of upheaval buckling, upheaval buckling will occur.

(2) When the pipe strain is less than the onset strain of upheaval buckling, further study is not necessary.

The following remarks should be noted.

(1) The onset of upheaval buckling is determined by comparing the pipe strain that occurs in a straight pipe having infinite length with the upheaval buckling start strain.

6.7.2 Onset of local buckling

When it has been determined that upheaval buckling will begin according to Section 6.7.1, "Determination of the onset of upheaval buckling, the pipe strain that occurs in the buckled portion is compared with the allowable strain (3%).

(1) When the pipe strain is greater than the allowable strain, it is determined that local buckling will begin.

(2) When the pipe strain does not exceed the allowable strain, further study is not necessary.

The following remarks should be noted.

(1) The onset of local buckling is determined comparing the pipe strain that occurs in the buckled portion of the straight pipe of infinite length after the onset of upheaval buckling at the allowable strain (3%).

(2) The portion in which upheaval buckling has occurred is replaced by a linear spring element and analysis is conducted changing the spring constant. Then, the conditions under which the amount of contraction in the buckled section balances the external force exerted due to ground displacement are obtained by repeated calculation. The strain that occurs in the buckled portion of the pipe after upheaval buckling has begun can thus be obtained .

(3) One possible method is as follows. The portion in which upheaval buckling has begun is replaced by a relationship between the axial compression obtained by using the partial analysis model and displacement. Then, the conditions under which the amount of contraction in the buckled section balances the external force exerted due to ground displacement are obtained. The strain that occurs in the buckled portion of the pipe after upheaval buckling has begun can thus be obtained. However, with this method, calculations do not converge in most cases and would depend on the conditions.

6.8 Straight pipe length to prevent buckling

When it has been determined that upheaval buckling will occur according to Section 6.7.1, "Determination of onset of upheaval buckling, the pipe strain induced in the buckled portion is compared with the allowable strain (3%).

(1) When the pipe strain is greater than the allowable strain, it is determined that local buckling will occur.

(2) When the pipe strain does not exceed the allowable strain, further study is not necessary.

The following remarks should be noted

(1) The portion in which upheaval buckling has begun is replaced by a linear spring element, and analysis is then conducted by setting the spring constant so that strain becomes 3% and changing

the straight pipe length, and then the straight pipe length at which the amount of contraction in the buckled section balances the external force exerted due to ground displacement is obtained.

(2) The conditions of connecting the bend to the end of the straight pipe should be set properly according to the number of bent pipes, angle, and other actual conditions.

(3) One possible method is as follows. The portion in which upheaval buckling has begun is replaced by a relationship between the axial compressive force obtained by using the partial analysis model and displacement, and analysis is conducted by changing the straight pipe length, and then the straight pipe length at which pipe strain that occurs in the buckled portion becomes equal to the allowable strain (3%) is obtained. However, with this method, calculations do not converge in most cases depending on the conditions.

(4) To be on the safer side than mitigating local buckling, the straight pipe length at which the generated pipe strain becomes equal to the onset strain of upheaval buckling is obtained. The seismic design can be conducted so as to avoid the straight pipe length from becoming equal to the obtained length.

(5) The upper limit value of the straight pipe length at which upheaval buckling will not begin can be obtained by multiplying the reference length by a reduction coefficient.

7. CONCLUSIONS

After the three year research program conducted by METI, the seismic design guidelines were drafted to mitigate upheaval buckling of small diameter pipes with the diameter of 4” and less and the upheaval buckling may be induced by strong ground shaking. Therefore the seismic integrity and the seismic diagnosis of pipes are discussed with respect to natural ground periods and length of straight portion of pipeline or distribution networks.

The fundamental data set used to the draft guidelines was obtained by the sand box tests and the field tests and finite element analysis. It should be mentioned that the draft seismic guidelines deals with pipes with the Plateau type or the Luders Elongation type materials as it was clarified by parametric finite element analysis that the pipes with the Round House type materials might not buckle in the upheaval mode.

Strong ground shaking has been assumed as the driving force of the upheaval buckling of small diameter pipes in this case. However permanent ground deformation such as lateral spreading or slope failure or slope movement may be possible causes of upheaval buckling of large diameter pipes. The finite element models, the global model and the local model, may be effective to simulate upheaval buckling behaviors and post-upheaval buckling behaviors.

ACKNOWLEDMENT

A series of investigation works was conducted to establish the seismic design guidelines to mitigate upheaval buckling of small diameter high-pressure gas pipelines and middle-pressure main distribution gas lines. The authors would like to thank the Ministry of Economy, Trade and Industry of Japan for permission to publish this paper. Also the authors would like to express sincere thanks to the members of the committee for their invaluable comments and advices.

REFERENCES

Japan Gas Association, JGA Guideline 2006-03 “Seismic design standard for high-pressure gas pipelines” (in Japanese), 2006.

METI, “Steering Committee Report of the Draft Seismic Design Guidelines to Mitigate Upheaval Buckling”, 2011. (in Japanese)