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New Seismic Design Criteria of Piping Systems in High-Pressure Gas Facilities

After the Great Hyogoken-nanbu Earthquake (1995), the Seismic Design Code for High-Pressure Gas Facilities of Japan was amended. This amended code requires two-step seismic assessments, that is, the evaluation of the Level 1 Required Seismic Performance for Level 1 earthquakes and that of the Level 2 Required Seismic Performance for Level 2 earthquakes. Seismic design of piping systems is newly included within the scope of the code. For Level 2 earthquakes, possible ground displacement due to liquefaction is taken into account. The evaluation method of the Level 1 Required Seismic Performance is specified in the amended code and that of the Level 2 Required Seismic Performance is proposed in the guideline. The evaluation of the former is based on elastic design and that of the latter on elastoplastic design. The propriety of the design criteria of piping systems with respect to ground displacement was confirmed by large deformation tests. In this paper, seismic design criteria of piping systems in the amended code and the evaluation method of the Level 2 Required Seismic Performance proposed in the guideline are introduced, and the results of the large deformation tests are reported.
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1 Introduction

Seismic design of high-pressure gas facilities such as towers and vessels had previously been carried out in accordance with MITI Notification 515 "Seismic Design Code for High-Pressure Gas Facilities" established in 1981 ([1]). The Great Hyogoken-nanbu Earthquake occurred in 1995 and the ground acceleration much beyond that of the Design Base Earthquake in the code was recorded. Some piping systems were damaged due to ground displacement (settlement and/or lateral movement) induced by liquefaction. Having learned from the experiences of the Great Hyogoken-nanbu Earthquake, the seismic design code was amended in 1997 ([2]).

In the amended code, both Level 1 and Level 2 earthquakes were considered, and the seismic design of a piping system was newly included within the scope of the code. A Level 1 earthquake is a probable strong earthquake occurring in the service life of the facilities, and a Level 2 earthquake is a possible strongest earthquake with an extremely low probability of occurrence. Facilities are required to remain safe without plastic deformation and without gas leakage against the ground acceleration of a Level 1 earthquake. In addition, they are also required to remain safe without gas leakage against the ground acceleration and possible ground displacement of a Level 2 earthquake. Plastic deformation is allowed in the case of a Level 2 earthquake. These seismic performances are called the "Level 1 Required Seismic Performance" (L1-RSP hereinafter) and the "Level 2 Required Seismic Performance" (L2-RSP hereinafter), respectively. The latter evaluation is applied only to facilities in the high importance category.

An evaluation method of L1-RSP for each structure is specified in the amended code. On the other hand, the evaluation methods of L2-RSP, including the estimation method of ground displacement, were investigated by committees organized in the High-Pressure Gas Safety Institute of Japan (KHK), and those methods were proposed in a guideline published by KHK ([3]). To ascertain the propriety of design criteria of piping systems with respect to ground displacement, large deformation tests using several piping models were carried out by KHK.

In this paper, we introduce the requirements in the new seismic design code, that is, the importance classification of a piping system, the design base earthquake, response analysis, response analysis against ground displacement and the evaluation method of the L1-RSP. Then, we introduce the evaluation method of the L2-RSP proposed in the guideline, and report the results of the large deformation tests.

2 Requirements in New Seismic Design Code

2.1 Importance Classification of Piping System

2.1.1 Importance Category of Piping. High-pressure gas facilities are classified into four categories, I a, I, II and III, according to three factors: the type of high-pressure gas, the inventory, and the distance from the outer surface of a facility to the boundary of the plant grounds. When the importance of a tower or a vessel (collectively called a vessel hereinafter) is higher than that of connecting piping, the importance of the piping is adapted to that of the vessel. This is based on the idea of preventing the contents of a vessel from leaking through damaged piping of lower importance.

2.1.2 Importance Category of Earthquake Shut-Off Valve. When an earthquake shut-off valve is installed in a piping system connected to a vessel and the importance of the valve is adapted to that of the vessel, the importance of the piping after the valve need not be adapted to that of the vessel. This is based on the idea that shutting off the piping right after an earthquake can fundamentally eliminate the possibility of the release of the contents of the vessel through the piping after the valve.

2.2 Design Base Earthquake. Seismic coefficients of a design base earthquake at the ground surface are described by Eqs. (1) and (2) in the code.

$$K_H = 0.150\mu_k\beta_1\beta_2\beta_3 \tag{1}$$

$$K_V = 0.075\mu_k\beta_1\beta_2\beta_3 \tag{2}$$

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Where K_H and K_V are the horizontal and vertical seismic coefficients of a design base earthquake at the ground surface, and β_1, β_2, β_3, and μ_k are the importance category factor (1.0–0.5), seismic zone factor (1.0–0.4 for Level 1 earthquakes, 1.0–0.7 for Level 2 earthquakes), site amplification factor (2.0–1.4), and earthquake level factor (1.0 for Level 1 earthquakes, 2.0 or over for Level 2 earthquakes), respectively. Response magnification curves are prepared corresponding to each seismic zone and soil profile type.

2.3 Response Analysis

2.3.1 Response Analysis of Supporting Structure. Seismic responses of supporting structures such as towers, vessels, and steel structures are analyzed by the modified static coefficient method or the response spectrum method. The static coefficient method is applicable for structures in lower importance categories (II and III) and relatively small in size.

2.3.2 Response Analysis of Piping System. Seismic responses of piping systems are analyzed by the modified static coefficient method or the response spectrum method. Response spectra given in the code are those for the seismic design of structures standing directly on the ground. Many piping systems are supported by supporting structures. Consequently, the modified seismic coefficient method is usually applied to piping systems.

2.3.3 Seismic Force of Piping System for Modified Seismic Coefficient Method. Seismic coefficients of a supporting structure in the horizontal and vertical directions at a pipe-supporting point are obtained by using

$$\mu K_{MH} = \mu \beta_5 K_H \tag{3}$$

$$K_{MV} = \beta_6 K_V \tag{4}$$

where μK_{MH} and K_{MV} are the supporting structure's horizontal seismic coefficient and vertical seismic coefficient at a supporting point and β_5, β_6, and μ are the horizontal response magnification factor, vertical response magnification factor, and horizontal seismic coefficient distribution factor, respectively. When the response spectrum method or the static coefficient method is applied to the supporting structure, the ratio of response acceleration at a supporting point to the acceleration of gravity or the seismic coefficient at a supporting point is substituted for the value of μK_{MH}.

Assuming that double the response acceleration of a structure at a supporting point is induced uniformly in a piping system, seismic force which acts on the piping system is expressed as

$$F_{MH} = \beta_8 \mu K_{MH} W_H \tag{5}$$

$$F_{MV} = \beta_9 K_{MV} W_V \tag{6}$$

where F_{MH} and F_{MV} are a design modified horizontal seismic force (*N*) and a design modified vertical seismic force which act on the piping system (*N*), β_8 and β_9 are the horizontal and vertical acceleration amplification factors (2.0 for both), and W_H and W_V are piping weights in the horizontal and vertical directions (*N*), respectively.

The seismic forces of a piping system in the modified static coefficient method are described by Eqs. (5) and (6) in the code. For valves, the acceleration amplification of 1.0 to 3.0 from the piping is considered.

Piping systems generally have the structural characteristics such as being supported at a number of points and high ductility. Owing to these characteristics, much damage in past earthquakes was due to relative displacement between supporting points while there was little damage due to the inertia force of the piping itself. On the basis of the criteria, it is considered that a piping system designed by considering an acceleration amplification of 2.0 from the supporting point will not be seriously damaged by an earthquake even if it resonates with the response wave of a structure.

2.4 Response Analysis Against Ground Displacement

2.4.1 Response Analysis of Foundation Against Ground Displacement. In evaluating the L2-RSP of a foundation, it is necessary to carry out response analysis by an adequate method taking into consideration liquefaction-induced ground displacement (called "ground displacement" hereinafter). It is also specified that the effect of ground shaking and ground displacement may be evaluated separately.

It was observed in past earthquakes that time lags occurred between the major ground shakings and the ground displacements. It was also observed during the Hyogoken-nanbu Earthquake that the amplification of acceleration from the base rock was relatively small in the surface soil where large-scale liquefaction was induced. These are background data of the judgment of the design criteria.

2.4.2 Piping Flexibility for Ground Displacement. It is specified that the piping connected to a vessel with an earthquake shut-off valve shall be fixed to a supporting structure after the valve on a common-foundation with the vessel. Otherwise, it shall be confirmed that the piping system is sufficiently flexible to withstand ground displacement. This design criterion is based on the idea that, if a piping is fixed to a supporting structure on a common-foundation, relative displacement does not arise between the nozzle and the fixed point even though ground displacement is induced by liquefaction around the foundation.

2.5 Stress Calculation and Allowable Stress for the Level 1 Required Seismic Performance Evaluation. Stress calculation methods and allowable stresses for the evaluation of L1-RSP of piping systems are summarized in Table 1.

Stress calculation formulas are fundamentally the same as those of ASME B31.3 "Process Piping," except that the effect of axial force is considered in calculating longitudinal stress. A stress range of double the yield point is allowed for cyclic loading.

In addition to the evaluation method by analysis, an easy substitutive method is prepared for piping in a lower importance category (II,III). This easy method includes a support span check against seismic force and a displacement-absorbing-capacity check against relative displacement (detail explanations are omitted here).

3 Evaluation of Level-2 Seismic Performenve

The evaluation method of the L2-RSP of piping systems is established to conform to the basic concept of the code and in consideration of the consistency with that of the L1-RSP.

3.1 Seismic Load

3.1.1 Design Seismic Force. Design seismic force is given by Eqs. (5) and (6).

3.1.2 Calculation of Response Displacement of Supporting Structure. In the evaluation of the L2-RSP of a facility, the Ultimate Design Method is usually applied (Shibata, [4]). In this evaluation method, the yield ratio (the ratio of plastic deformation to yield deformation) is calculated for each failure mode. Therefore, fundamentally, it is possible to obtain the maximum displacement at each elevation by investigating every failure mode of the facility. However, this method is not convenient. It is considered that the displacement expressed as Eq. (7), in which the distribution curve of plastic deformation is approximated by that of elastic deformation, may be used as the design displacement of the L2-RSP evaluation of a piping system.

$$\delta_x = \begin{cases} (1+\mu_p)\dfrac{K_y}{K_{MH}}\delta_{xMH}, & \mu_p > 0 \\ \delta_{xMH}, & \mu_p = 0 \end{cases} \tag{7}$$

Where δ_x, δ_{xMH}, μ_p, K_y, and K_{MH} are the response horizontal displacement at a supporting point (mm), response horizontal dis-

Table 1 Stress calculation and allowable stress for evaluation of Level 1 Seismic Performance

Stress calculation and allowable stress

Piping

Longitudinal stress due to internal pressure, weight and design seismic force

$$\sigma_t = \frac{\sqrt{(i_i M_i)^2 + (i_o M_o)^2}}{Z} + \left|\frac{F}{A}\right|$$

σ_t : Longitudinal Stress (N/mm^2)
i_i, i_o : In-plane and out-of-plane stress intensification factors
M_i, M_o : In-plane and out-of-plane bending moments due to internal pressure, weight and design seismic force (N·mm)
Z : Section modulus of pipe (mm^3)
F : Axial force (N)
A : Cross-sectional area of pipe (mm^2)

Resultant stress range due to design seismic force and movement of support

$$\sigma_E = 2\frac{\sqrt{(i_i M_i)^2 + (i_o M_o)^2 + M_t^2}}{Z}$$

σ_E : Cyclic stress range due to design seismic force and movement of support (N/mm^2)
M_i, M_o, M_t : In-plane, out-of-plane and torsion moments due to design seismic force and movement of support (N·mm)

Allowable stress

Type of Stress	Allowable stress
Longitudinal stress	S
Cyclic stress range	$2S_y$

Flange (Class Ia, I only)

Stresses due to design seismic force and movement of support
Stresses are calculated according to JIS B2205 「Calculation of pipe flange」 substituting internal pressure by gross equivalent internal pressure

$$P_{eq} = P + P_e$$

$$P_e = \frac{4F}{\pi D_e^2} + \frac{16M}{\pi D_e^3}$$

P_{eq} : Gross equivalent internal pressure (MPa)
P : Internal pressure (MPa)
P_e : Internal pressure equivalent to seismic load (MPa)
F : Axial force due to seismic load (N)
M : Bending moment due to seismic load (N·mm)
D_e : Mean diameter of gasket contacting surface (mm)

Allowable stress

Type of Stress	Allow. stress
Radius stress in flange	S
Circumferential stress in flange	S
Axial stress in hub	$2S_y$

Valve

Stress due to design seismic force when the weighty driving part is not supported

$$\sigma_n = \frac{F_{MH} L_b}{Z} + \sigma_L$$

σ_n : Stress arise in cross-sectional area between valve body and weighty driving part (N/mm^2)
F_{MH} : Seismic force (N)
L_b : Distance from the cross-sectional area to the center of weighty driving part (mm)
Z : Section modulus (mm^3)
σ_L : Stress due to internal pressure and driving force (N/mm^2)

Allowable stress

Type of valve	Allow. stress
Class Ia, I Earthquake shut-off valve	0.5S
Other valves	S

Expan-sion joint

Maximum axial stress amplitude of expansion joint
Maximum axial stress amplitude of flexible joint shall be calculated according to JIS B2352 「Bellows type flexible joint」.

Allowable stress
Two times the allowable stress amplitude obtained from chart in JIS B8251「Stress and fatigue analysis of pressure vessel」 corresponding to design cycle number 500.

Nozzle (Class Ia, I only)

Allowable stress

Stress intensity	Allow. stress
Primary general membrane stress intensity	S
Primary local membrane plus primary bending stress intensity	1.5S
Difference of maximum and minimum value at cycle of primary local membrane plus primary bending plus secondary stress intensities	$2S_y$

Standard allowable stress S for the seismic design of pressure part

Type of material	S
Aluminum alloy or alloy steel containing 9% nickel used at temperatures lower than room temperature	The smallest of the followings (1) $0.6S_u$ (2) $0.9S_y$
Austenite stainless steel and high-nickel alloy used at temperatures higher than room temperature	ditto (1) $0.6S_{uo}$ (2) $0.6S_u$ (3) $0.9S_{yo}$ (4) S_y
Others	ditto (1) $0.6S_{uo}$ (2) $0.6S_u$ (3) $0.9S_{yo}$ (4) $0.9S_y$

S_u : Tensile strength at the design temperature (N/mm^2)
S_{uo} : Minimum tensile strength at room temperature (N/mm^2)
S_y : Yield point or 0.2% endurance strength at the design temperature (N/mm^2)
S_{yo} : Minimum yield point or 0.2% endurance strength at room temperature (N/mm^2)

Movement of support : Movement of support point due to response displacement of supporting structure

placement of the structure at a supporting point corresponding to the design modified horizontal coefficient (mm), plastic response ratio of the mode, where the plastic response ratio is the largest of all the failure modes, the yield seismic coefficient, and the design modified horizontal seismic coefficient, respectively.

For a steel structure, the displacement of each floor is obtained by adding the layer displacement, calculated by considering the plastic deformation, to the displacement of the lower floor.

3.1.3 Calculation of Foundation Displacement. During the Great Hyogoken-nanbu Earthquake, large scale liquefaction occurred at reclaimed land near the seaside and subsequent ground settlement extended to 70 to 80 centimeters. At the seaside, gravity-type quay walls moved several meters toward the sea and the liquefied ground landward of the quay walls flowed toward the sea at the same time. The effect of the movement of the quay walls extended to the land nearly one hundred meters from the sea, though the amount of ground displacement decreased with increasing distance.

After this earthquake, the method of estimating the amount of ground displacement and the response analysis method of a foundation were investigated by a committee organized in the KHK and some methods were proposed in their guideline ([3]). According to the results of this investigation, the amount of ground displacement depends on the soil conditions, the type of quay wall and the configuration around the quay wall. Finally, the estimated maximum value of ground displacement in the worst case was three meters. This value is nearly equal to the actual displacement caused by the Great Hyogoken-nanbu Earthquake. The amounts of settlement, irregular settlement and horizontal displacement of a foundation are calculated taking into consideration factors such as the existence of piles, length of piles, the depth of liquefied layer, and liquefied soil properties, and the distance from the quay wall. From the results of response analyses of the foundation with respect to ground displacement, the displacement of the structure at the pipe support point can be calculated.

3.2 Response Analysis

3.2.1 Method of Analysis. Nonlinear FEM (finite element method) analysis is very effective for analyzing the plastic response behavior of a piping system. However, this method is not popular in ordinary piping design. A simplified method called the modified flexibility factor method was investigated for designers' convenience.

3.2.2 Modified Flexibility Factor Method. An elbow, precisely speaking, a corner composed of an elbow and adjacent short parts of straight pipes, has plastic deformation capabilities such as absorption of large angular displacement with relatively small local strain under a bending moment smaller than the fully plastic moment of a straight pipe. This implies that the nonlinear behavior of piping systems can be analyzed, as long as the straight pipe shows almost linear behavior, by taking into consideration the nonlinear characteristics of only elbows.

Modified flexibility factors of the elbow in the plastic deformation range and an approximate formula which shows the relationship between angular displacement and equivalent plastic strain have been derived at KHK (Mukaimachi, [5]).

Flexibility factors in the three bending directions differ from each other, and the restoring moment of opening in-plane bending is the highest among them. Average flexibility factor seems to be reasonable for the analysis with respect to seismic force and response displacement at a support point, which are applied repeatedly to the piping system. The flexibility factor of the corresponding bending direction is adequate for analysis with respect to the ground displacement, which is not loaded repeatedly. Adoption of the flexibility factor of opening in-plane bending is conservative, but a reaction force may be overestimated. The modified flexibility factor method is considered to be applicable, keeping in mind these characteristics.

There is another matter to be considered in the piping design and flexibility analysis for ground displacement. When a straight pipe with a length of 1 tilts at an angle of θ, the end moves to a point of different coordinates and the length of the component in the original axial direction decreases by $1(1-\cos\theta)$. This effect, due to geometrical nonlinearity, on piping flexibility is negligible so long as the angle is small and it is disregarded in a conventional analysis method. However, it cannot be neglected when the angle is large. A piping system must have sufficient flexibility to absorb a relative displacement due to this effect in the case of large deformation. This must be kept in mind whichever analytical method is adopted.

3.3 Securing Piping Flexibility for Ground Displacement. Generally, it is not easy to secure high piping flexibility while providing supports to reduce the effect of weight and seismic force. It is known that a time lag occurs between the main ground shaking and ground displacement. Based on this experience, an acceptable design method is to allow some supports to lose their restraining functions with the progress of relative displacement due to ground displacement, in order to guarantee the required piping flexibility for large relative displacement.

Figure 1 shows an actual example of piping observed after the Great Hyogoken-nanbu Earthquake. The combination of a straight pipe perpendicular to the direction of forced displacement (forward the right) and elbows at the both ends absorbed a large amount of relative displacement. Furthermore, elevating the on-ground straight pipe after the elbow enabled accompanying relative displacement in the vertical direction to be absorbed. This actual example suggests an effective design concept to prepare for ground displacement and also shows the feasibility of the modified flexibility factor method.

3.4 Allowable Limit. The following failure modes of a piping system due to seismic force, response displacement of supporting structure and ground displacement are expected.

1. Large plastic deformation of elbow and cracking of elbow due to fatigue or large strain
2. Cracking at local discontinuity in a tee due to fatigue or large strain
3. Cracking at local discontinuity in straight pipe at supporting point due to fatigue or large strain
4. Ratcheting due to cyclic load under internal pressure
5. Leakage from flanged joint due to excessive bending moment
6. Cracking of bellows due to fatigue or large strain
7. Cracking at local discontinuity around nozzle due to fatigue or large strain
8. Collapse, buckling or excessive deformation of support due to reaction force and damage to pipe resulting from loss of supporting function
9. Plastic deformation of extension rod of shut-off valve and valve malfunction

To prevent these failures in the event of a Level 2 earthquake, allowable limits are established for each component, as shown in Table 2.

An allowable plastic strain range of single amplitude 2% for cyclic loading is proposed in consideration of the extremely low probability of occurrence of a Level 2 earthquake. This proposed value still leaves room for further study. An allowable plastic strain range of single amplitude 5% for loading of ground displacement, which has some margin for single cyclic loading, is proposed to prepare for unexpected behavior of ground displacement and also to control detrimental movement of a piping system.

The allowable angular displacements derived from case studies by FEM analysis at KHK (Mukaimachi, [5]) are considered to be acceptable. The formula for evaluating leakage from a flanged joint derived from experimental studies at KHK (Ando, [6]) is also considered to be acceptable. The evaluation of the valve is considered unnecessary because the allowable stress for a Level 1 earthquake is low and also because the reliability of earthquake shut-off valves was verified by a series of tests conducted by KHK in 1996.

.3.5 Substitutive Method. It is specified in the code, when considering ground acceleration, that the evaluation of the L1-RSP for seismic coefficients which are half those of a Level 2 earthquake can be substituted for the evaluation of the L2-RSP. This is a simplified method based on the Ultimate Design Method considering the energy absorption capability of a structure. This method is consistently applicable to a piping system. When this method is adopted, the L1-RSP is evaluated against the supporting structure's seismic coefficients and response displacement obtained by the substitutive method.

4 Seismic Performance Test of Piping System

4.1 Purpose of Test. Ground settlement extending several tens of centimeters or more was not considered in the past piping design. Horizontal relative displacement extending several tens of centimeters or more due to lateral ground movement was also not considered. The purpose of the present tests is to confirm the feasibility of piping design aimed at absorbing large relative displacement due to ground displacement, the propriety of design criteria against ground displacement and the propriety of the general idea of the modified flexibility factor method. We also aim to confirm the movement of piping in which an expansion joint (universal type) is included, under the loading condition that a relative displacement exceeding the absorption limit of the joint is imposed.

4.2 Test Model

4.2.1 Selection of Piping System for Test. A typical example of piping in a high importance category is the receiving piping connected to a low-temperature double-wall flat-bottom tank containing a large amount of liquefied gas. This type of tank is usually constructed near the seaside for the convenience of unloading. This receiving piping was selected as a test model. The nozzle for this type of tank has the characteristics that it moves in the axial direction with contraction of the inner shell during the initial cold operation and then inclines downward with the swelling of the lower part of the inner shell under a liquid head load. These characteristics are also considered in determining the shape of the piping model.

The following three types of systems are considered as means of eliminating or mitigating the effect of ground displacement.

1. *Common-foundation fixed-support system*: The effect of ground displacement is eliminated by preparing a fixed-support point on a common-foundation and installing an

Table 2 Allowable limit for evaluation of Level 2 Seismic Performance

Piping — Allowable Limit

Allowable limit (Seismic force and movement of support)

Type of strain	Allowable limit
Longitudinal stress due to internal pressure, weight, seismic force and movement of support	Limit of internal pressure ratcheting
Range of cyclic strain due to seismic force and movement of support	Plastic strain single amplitude 2%

Allowable limit (Ground displacement)

Type of strain	Allowable limit
Plastic strain due to ground displacement	Plastic strain single amplitude 5%

The following may be substituted for the above.

Allowable limit (Seismic force and movement of support)

(Elbow)

Type of stress	Allow. limit
Cyclic strain range due to seismic force and movement of support	θ_a
θ_a : Angular displacement corresponding to maximum equivalent plastic strain single amplitude 2% (degrees)	

(Straight pipe, tee and others)

Type of stress	Allow. limit
Longitudinal stress due to internal pressure, weight, seismic force and movement of support	2S
Cyclic stress range due to seismic force and movement of support	$4S_y$

Allowable limit (Ground displacement)

(Elbow)

Type of strain	Allow. limit
Strain due to ground displacement	θ_a
θ_a : Angular displacement corresponding to maximum equivalent plastic strain 5% (degrees)	

(Straight pipe, tee and others)

Type of stress	Allow. limit
Stress due to ground displacement	$4S_y$

Flange — **Leak evaluation**

$$mp + \alpha p_e \le \sigma_a$$

m : Gasket constant
p : Internal pressure (MPa)
p_e : Seismic-load-equivalent internal pressure (MPa)
α : Leak effect compensation factor corresponding to equivalent pressure (=0.75m)
σ_a : Gasket stress due to initial tightening force (N/mm^2)

Expansion joint — **Allowable stress**

Seismic load	Cyclic number
Seismic force and movement of support	50
Ground displacement	10

Expansion joint must have sufficient strength to withstand reaction force which arises from relative displacement which does not correspond to the effective direction of the joint.

Nozzle — **Allowable limit (Seismic force and response displacement)**

Stress intensity	Allow.limit
Primary local membrane plus primary bending stress intensity	3S
Difference of maximum and minimum value at cycle of primary local membrane plus primary bending plus secondary stress intensities	$4S_y$

Allowable limit (Ground displacement)

Stress intensity	Allow.limit
Primary bending stress intensity	$4S_y$

Support — **Allowable limit**

Support	Allowable limit	
Fix support	$F < F_y$	(1)
Guide support	$F < F_{L1}$, when deformation is functionally allowable $F < F_y$, when deformation is functionally unallowable	(1)
Release support	$F < F_{L1}$ for seismic force and movement of support $F > F_{L2}$ for ground displacement	

F : Reaction force (N) F_y : Yield strength (N)
F_{L1} : Minimum limit strength (N)
F_{L2} : Maximum limit strength (N)

(1) : Allowable stress method in Level 1 Seismic Performance Evaluation is applicable.

Movement of support : Movement of support point due to response displacement of supporting structure

earthquake shut-off valve between the vessel and the support. To mitigate the reaction force to the support, the piping system after the support is so designed that relative displacement due to ground displacement is absorbed by a combination of elbows and straight pipes.

2. *Common-foundation nonfixed-support system*: Relative displacement due to ground displacement is absorbed by the same method as in the above system, while providing a loop to assure flexibility for ordinary operation. The loop is supported vertically or horizontally at points on the common-foundation for each expected ground displacement direction so that little bending moment caused by ground displacement is transferred to the shut-off valve, while taking care not to restrain the free movement of the loop under ordinary operation.
3. *Expansion joint included system*: Relative displacements due to both nozzle movement and ground displacement are absorbed by a universal-type expansion joint included in the piping system.

Schematics of these piping systems are shown in Fig. 2. A relative displacement in the vertical direction is assumed between the vessel foundation and local support foundations, and that in the horizontal direction is supposed between the vessel foundation and the foundation of a supporting structure near the quay wall. The amount of settlement of a tank foundation without piles depends on factors such as the level of sand compaction, bottom area, and weight (liquid level at an earthquake), and is not necessarily greater than that of local foundations.

4.2.2 Dimensions of Test Model. Tests were carried out separately for the three relative displacement directions. The models of each type of piping system, 1 to 3 described above, are called F series (F-V,F-H1,F-H2), NF series (NF-V,NF-H1,NF-H2), and U series (U-V,U-H1,U-H2), respectively.

The dimensions of test models are shown in Fig. 2. One end of each test model is fixed to the support on a common-foundation for F series, and to a vessel nozzle for NF and U series. The other end is the first support point for the F-V model (settlement of the foundation of local support is smaller than that of the vessel), the first turning point for NF-V and U-V models (vice versa), the second turning point toward the quay wall for H1 models (F-H1,NF-H1,U-H2), and an intermittent point toward the quay wall for F2 models (F-H2,NF-H2,U-H2). Consequently, the second end in F-H1, NF-H1, and U-H1 models is assumed to be an elbow and is expected to be nearly a hinge point at large deformation. Each piping system is assumed to be restrained in the axial direction by a supporting structure near the quay wall. The ends of piping models are the loading points in the tests. A short pipe is connected to the end of each H2 model for convenience of test.

A flanged valve and a flanged dummy valve or two dummy valves, representing a block valve and an earthquake shut-off valve, are installed near the fixed point for NF and U series. For F series, each piping model is welded to the fixed point with no flange.

No test model is restrained horizontally at the release support point under the assumption that the support would lose its restraining function against reaction force as expected. No U series model is also restrained at the support point near the expansion joint considering the primary object of test. Movement of expansion-joint-included system with is restrained vertically at the

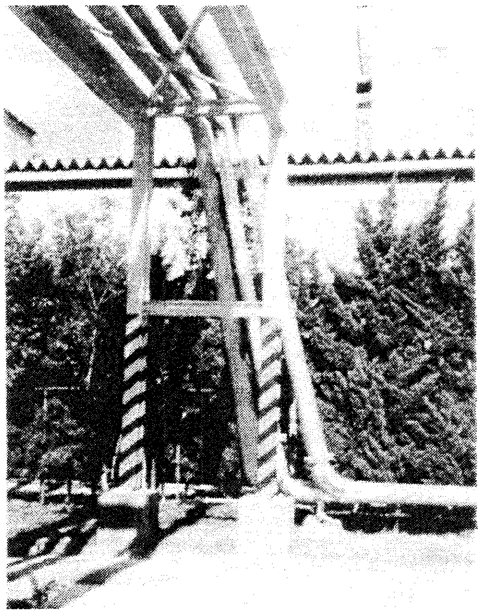


Fig. 1 Plastic deformation of piping systems which absorbed large relative displacements—The Great Hyogoken-nanbu Earthquake (photo by Mr. Tanoue)

support point near the expansion joint under relative displacement load in vertical direction can nearly be confirmed by U-H2 model test.

Piping specifications are 6 B (150A, Do = 165.2 mm), STPG370 (carbon steel pipe), PT370 (carbon steel elbow), schedule 40 (t = 7.1 mm), and Class 150# in flange pressure-temperature rating. The expansion joint is a standard type, 2000 mm in length, which is designed to absorb a relative displacement of 200 mm for design cyclic number of 500. The model size is half that of the receiving piping system of a 4×10^4 kl-class storage tank.

4.3 Test Procedure

4.3.1 Test Procedure. Displacements, strains, reaction forces and internal pressure were measured, while forced displacement was loaded monotonically using a hydraulic jack. Internal pressure was held constant at 0.2 Mpa. A pin joint was used at the loading point. Movement of the loading point in the direction perpendicular to the loading direction was restricted by connecting a long rod (5–7.5 m in length). This boundary condition is acceptable for test purposes, though it varies in practice depending on the restrictive condition around the loading point. Figure 3 shows the setup of the test.

4.3.2 Nonlinear Finite Element Analysis. To support the evaluation of the test results, physically and geometrically nonlinear analyses were performed by using the nonlinear finite element analysis code "ABAQUS" for F and NF series piping models. Elbow A, B, C, and the adjacent parts of straight pipes (max. 5 times the pipe diameter in length) were modeled by three-dimensional shell elements, and other sections were modeled by beam elements. Nominal thickness was used in models of pipes and elbows. Properties of elbow material, determined by tensile tests, were used for both pipes and elbows. Yield point, young's modulus and Poisson's ratio are 340.1 N/mm^2, 199,000 N/mm^2 and 0.3, respectively, and the engineering stress-strain curve is as shown in Fig. 4.

4.4 Test Result.

Deformation shapes of piping systems with main measured data at the final stages of tests are shown in Fig. 5. Analytical results are also shown. Transitions of the deformation of U-series models are shown in Fig. 6. Force-displacement curves (F, NF, and U series), relationships between forced displacement and principal strains at the measured point (F and NF series) and relationships among displacement, internal pressure and axial forces of flange bolts (U-H1,U-H2) are shown in Fig. 7.

4.4.1 Test Result for F and NF Series Piping Model.

1. No leakage was observed in any test model.
2. Plastic deformation was concentrated at corners (elbows and adjacent short connecting pipes) and was not found anywhere else on the straight pipe. Deformation modes of piping systems were as expected.
3. Little effects of forced displacement were recognized in the part around the earthquake shut-off valve in the case of NF series piping models.
4. The results of the nonlinear FEM analysis, such as displacements of representative points, reaction force of piping model at the loading point, and plastic strains at measured points, coincided

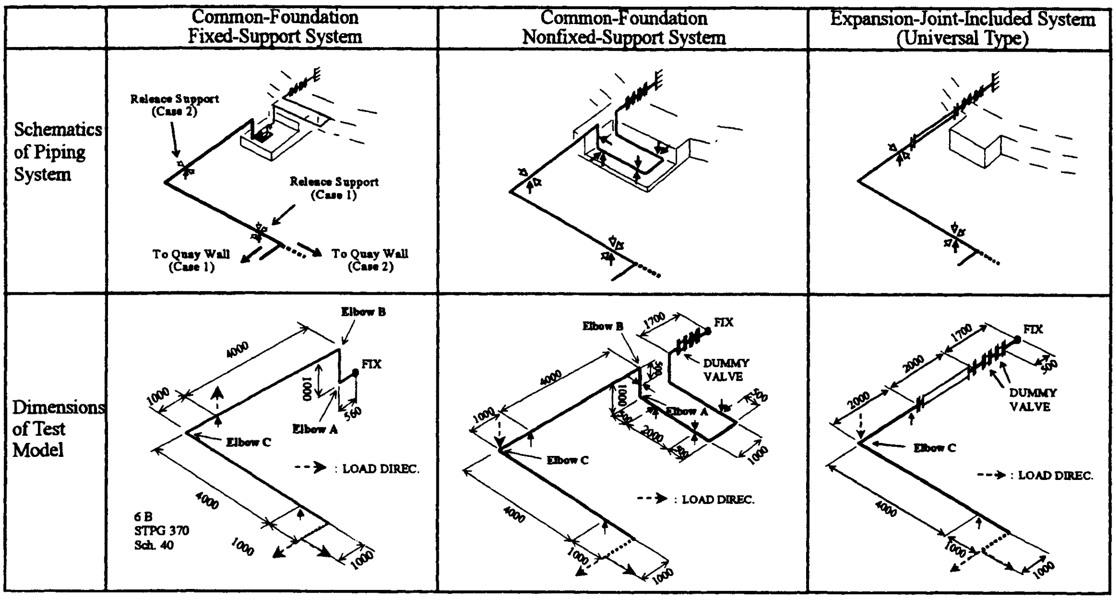


Fig. 2 Schematics of piping systems and dimensions of test models

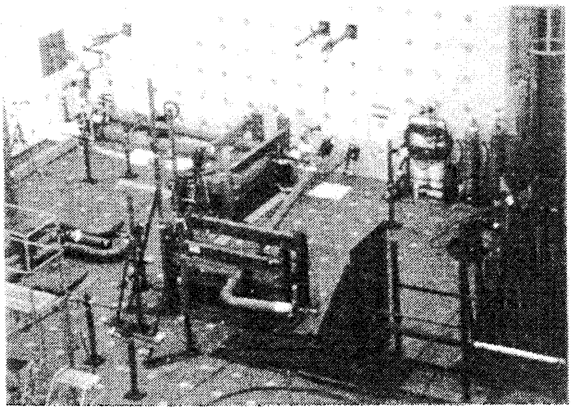


Fig. 3 Setup of test

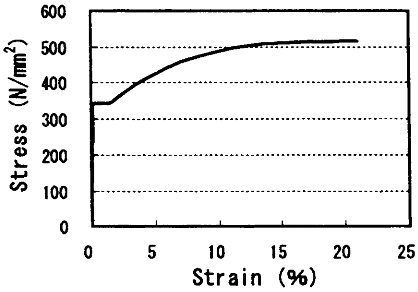
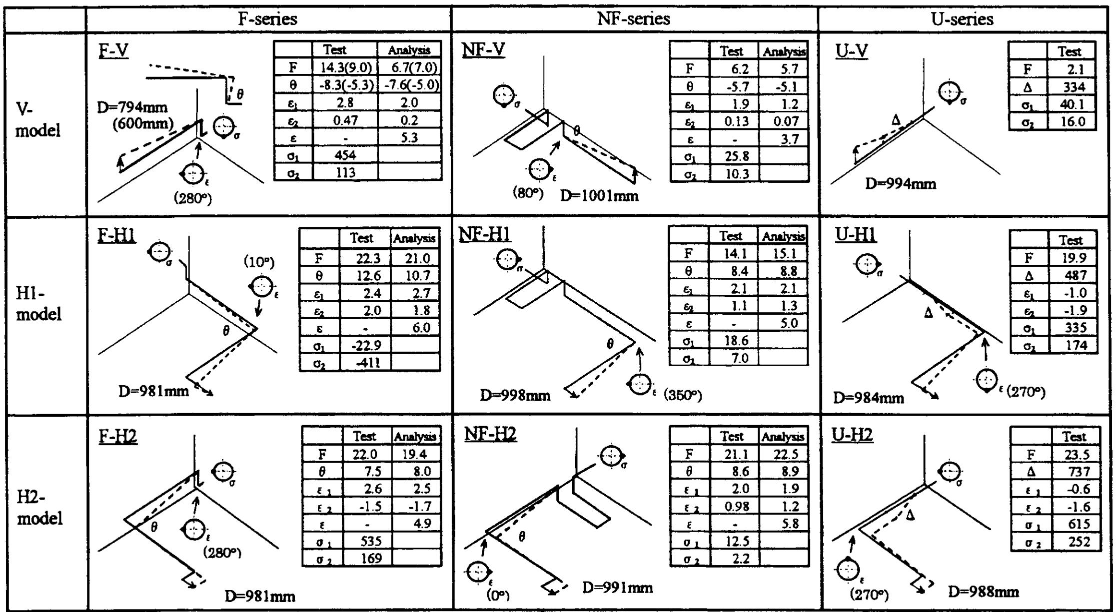


Fig. 4 Engineering stress-strain curve of elbow material



F-V

	Test	Analysis
F	14.3(9.0)	6.7(7.0)
θ	-8.3(-5.3)	-7.6(-5.0)
ε_1	2.8	2.0
ε_2	0.47	0.2
ε	-	5.3
σ_1	454	
σ_2	113	

NF-V

	Test	Analysis
F	6.2	5.7
θ	-5.7	-5.1
ε_1	1.9	1.2
ε_2	0.13	0.07
ε	-	3.7
σ_1	25.8	
σ_2	10.3	

U-V

	Test
F	2.1
Δ	334
σ_1	40.1
σ_2	16.0

F-H1

	Test	Analysis
F	22.3	21.0
θ	12.6	10.7
ε_1	2.4	2.7
ε_2	2.0	1.8
ε	-	6.0
σ_1	-22.9	
σ_2	-411	

NF-H1

	Test	Analysis
F	14.1	15.1
θ	8.4	8.8
ε_1	2.1	2.1
ε_2	1.1	1.3
ε	-	5.0
σ_1	18.6	
σ_2	7.0	

U-H1

	Test
F	19.9
Δ	487
ε_1	-1.0
ε_2	-1.9
σ_1	335
σ_2	174

F-H2

	Test	Analysis
F	22.0	19.4
θ	7.5	8.0
ε_1	2.6	2.5
ε_2	-1.5	-1.7
ε	-	4.9
σ_1	535	
σ_2	169	

NF-H2

	Test	Analysis
F	21.1	22.5
θ	8.6	8.9
ε_1	2.0	1.9
ε_2	0.98	1.2
ε	-	5.8
σ_1	12.5	
σ_2	2.2	

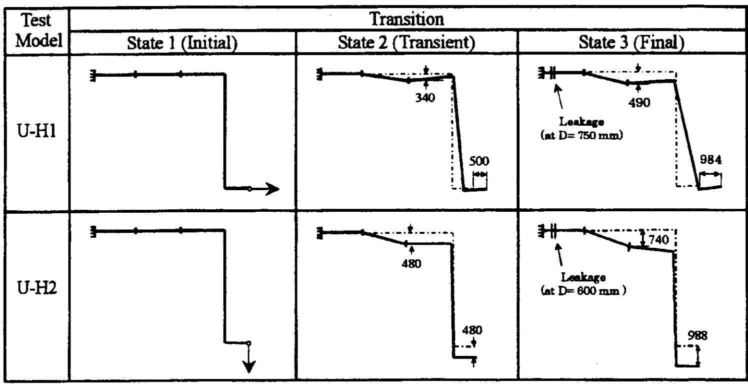
U-H2

	Test
F	23.5
Δ	737
ε_1	-0.6
ε_2	-1.6
σ_1	615
σ_2	252

D : Forced displacement (mm)
F : Restoring force of piping system against displacement load (kN)
θ : Angular displacement of elbow which showed maximum value (not including component of connecting pipe contributing to global angular displacement of corner) (degree)
ε_1, ε_2: Principal strain 1 , 2 at a measured point of elbow (%)
ε : Maximum value of equivalent plastic strain in elbow (%)
σ_1, σ_2 : Principal stress 1 , 2 at a measured point of pipe close to the fixed point (N/mm²)
Δ : Relative displacement of flexible joint between two ends (mm)

1. Strain gages were adhered to the four points on circumference at the center of major elbows and on a straight pipe close to the fixed point. A dot in cross section indicates the point where the maximum value as a principal strain or stress was measured, viewed from loading side. As for elbows, three strain gages were adhered to each point at intervals of an angle of 10 degrees and the exact position where maximum value was measured is also noted by clockwise angle in degrees from the belly of an elbow.
2. The cause of the difference between restoring forces in test and analysis at final stage of F-V model test was due to the loading device. [Refer to Note (1) in Fig.7]

Fig. 5 Results of large deformation tests and comparison with analytical results



Explanation

1. From state 1 to state 2, forced displacement was absorbed by an expansion joint. Reaction force was relatively small. {Fig. 7 (14), (15)}
2. After the expansion joint reached its mechanical absorption limit (state 2), restoring force suddenly increased and absorption of forced displacement was gradually shifted to that by the flexibility of piping itself. {Fig. 7 (14), (15)}
3. With the sudden increase of restoring force, axial force of bolts of a valve flange next to the fixed point started increasing. The rising curve of U-H2 model was steep compared with that of U-H1 model. Leakage from the flanged joint was observed when forced displacement reached 600 mm in the case of U-H2 model and 750 mm in the case of U-H1 model. {Fig. 7 (16), (17)}

Fig. 6 Transition of deformation of expansion-joint-included piping system

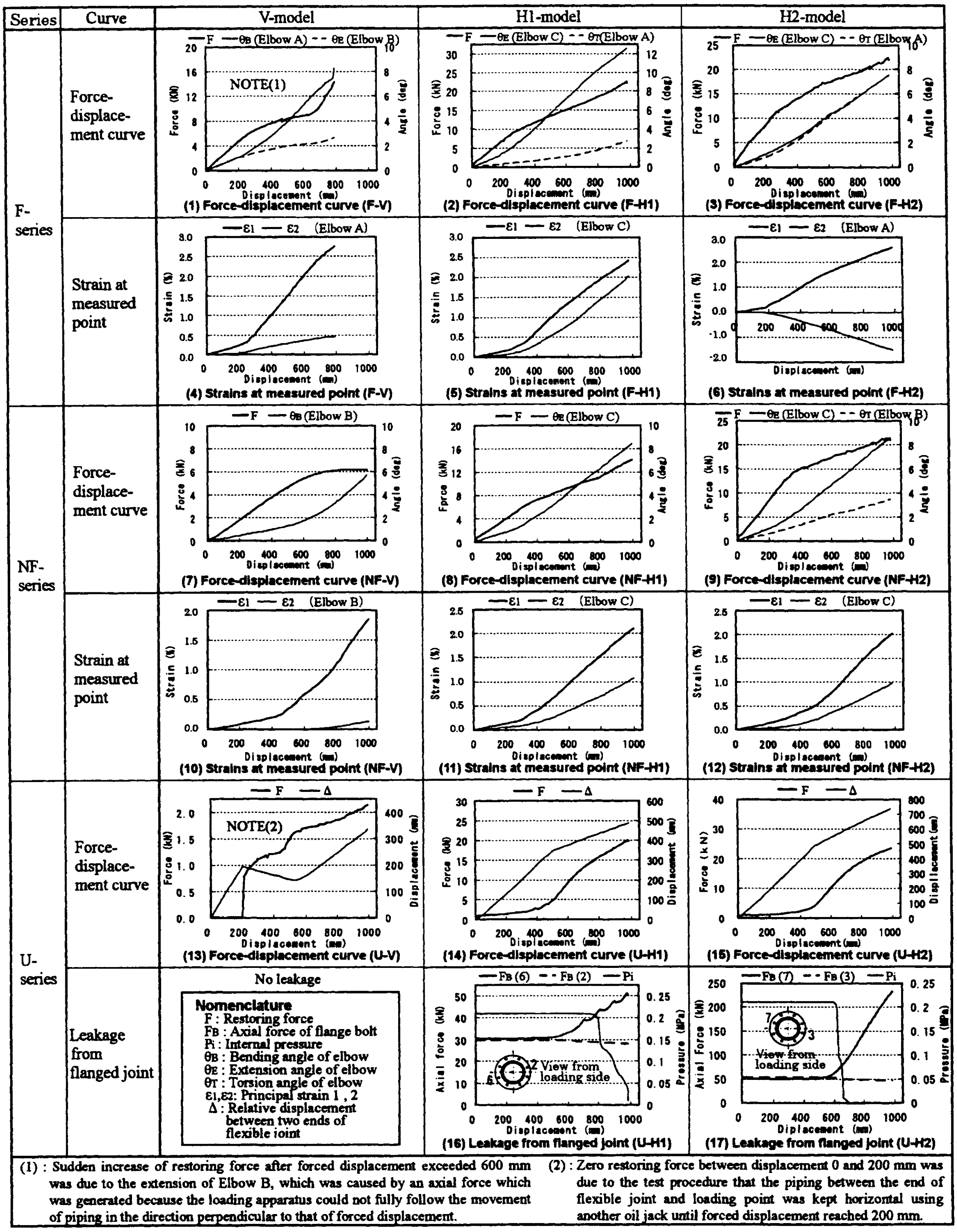


Fig. 7 Force-displacement curves and other displacement-dependent data

well with the test results. The maximum value of equivalent plastic strain in the elbow was 4 to 6% by the nonlinear FEM analysis, which is at a comparable level with the allowable plastic strain (5%) recommended in the guideline.

4.4.2 Test Results of U Series Piping Model.

1. In the case of H2 model, where the effective direction of the expansion joint corresponded to that of forced displacement and piping after the expansion joint had little flexibility in the same direction leakage from the flanged joint near the fixed point was observed soon after forced displacement reached the mechanical absorption limit of the expansion joint.
2. In the case of H-1 model, where the axial direction of the expansion joint corresponded to that of forced displacement and piping after the expansion joint had some flexibility in the same direction, axial load due to forced displacement was mitigated by piping flexibility but forced displacement was accompanied by lateral and angular displacement of

piping at the connection of the expansion joint. And, leakage of the same pattern with U-H2 model was observed in the course of time.

4.5 Conclusions of Test Results

1. Both design concepts of a common-foundation fixed-support system and a common-foundation nonfixed-support system are effective in protecting an important part of a piping system against ground displacement.

2. Designing a piping system to absorb large relative displacement due to ground displacement is possible within the range of the allowable plastic strain limit of 5%, by utilizing a combination of straight pipes and elbows and adopting release supports as needed.

3. The general idea of considering only nonlinear characteristics of elbows in the modified flexibility factor method is reasonable. The elbow's characteristic includes the effect of oval deformation of the short part of a connecting pipe, which contributes to the increase of angular displacement of the corner. However, the effect of geometrical nonlinearity must be considered separately in the case of large deformation.

4. When an expansion joint is included as a means of absorbing large displacement due to ground displacement, it is recommended leaving margin by providing supplementary piping flexibility to prepare against relative displacement which might exceed the absorption limit of the joint.

5 Conclusions

In the amendment of the Seismic Design Code for High-Pressure Gas Facilities of Japan after the Great Hyogoken-nanbu Earthquake, seismic design of a piping system was included within the scope of the code. Basic requirements and the evaluation methods of the Level 1 Required Seismic Performance for Level 1 earthquakes were specified in the amended code. The evaluation methods of the Level 2 Required Seismic Performance for Level 2 earthquakes were proposed in the guideline. Possible ground displacement due to liquefaction is taken into account for Level 2 earthquakes. A design that allows some supports to lose their restraining functions against relative displacement due to ground displacement was considered to be acceptable. Large deformation tests were carried out using several models of the receiving piping of a low-temperature flat-bottom tank. Tests confirmed that the design concept of eliminating or mitigating the effect of ground displacement by adopting a common-foundation is effective and that the design of a piping system, which absorbs large relative displacement due to ground displacement, is possible within the allowable plastic strain limit of 5%. It was also confirmed that the general idea of considering only elbow's nonlinear characteristics in the modified flexibility factor method is reasonable. Also, supplementary piping flexibility is recommended for a piping system in which an expansion joint is included, to leave a margin against ground displacement.

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