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IMPROVEMENT OF THE DAMPING CONSTANTS FOR SEISMIC DESIGN OF PIPING SYSTEM FOR NPP

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ABSTRACT

The present design damping constants for nuclear power plant (NPP)'s piping system in Japan were developed through discussion among expert researchers, electric utilities and power plant manufactures. They are standardized in "Technical guidelines for seismic design of Nuclear Power Plants" (JEAG 4601-1991 Supplemental Edition). But some of the damping constants are too conservative because of a lack of experimental data.

To improve this excessive conservatism, piping systems supported by U-bolts were chosen and U-bolt support element test and piping model excitation test were performed to obtain proper damping constants.

The damping mechanism consists of damping due to piping materials, damping due to fluid interaction, damping due to plastic deformation of piping and supports, and damping due to friction and collision between piping and supports. Because the damping due to friction and collision was considered to be dominant, we focused our effort on formulating these phenomena by a physical model.

The validity of damping estimation method was confirmed by comparing data that was obtained from the elemental tests and the actual scale piping model test. New design damping constants were decided from the damping estimations for piping systems in an actual plant.

From now on, we will use the new design damping constants for U-bolt support piping systems, which were proposed from this study, as a standard in the Japanese piping seismic design.

INTRODUCTION

The current damping constants for seismic design of NPP piping systems were developed as a result of discussions between expert researchers, representatives of electric utilities and power plant manufacturers, and have been standardized as "Technical Guidelines For Seismic Design of Nuclear Power Plants" (JEAG 4601-1991 Supplemental Edition).

The current design damping constants were defined from the damping constants of actual piping systems based on the damping estimation method. However, the damping constants for design are thought to be established at low values in comparison with the actual damping constants, because they have not included damping effects of non-linear phenomena, which were left in the future task, such as dispersion energy caused by collision at the support structure.

This study focused on the damping constants of the piping system supported by U-bolts to improve the current damping constants for design as more appropriate values.

PRESENT DAMPING CONSTANTS FOR SEISMIC DESIGN

From the period of construction of Japan's first NPP in the second half of the 1960s to the establishment of the current damping constants for seismic design of piping systems, the standard value for the damping constant in general use was 0.5%.

Since 1984, the damping constants as shown in Table 1 for design of piping systems have been defined on the basis of type of support structure and presence or absence of thermal insulation[1]. However, the damping constant of the piping system supported by U-bolt has been paid no attention. It has the damping effects such as friction and collisions between the support structure and pipe, and the damping constant was thought to be low in comparison with actual value.

OUTLINE OF JOINT RESEARCH

Background of Research

As Table 1 indicates, values of between 0.5% and 2% are used for piping without thermal insulation as damping constants for design of piping systems specified in the JEAG 4601-1991 Supplemental Edition. These values vary depending on the classification of the piping system by type and the number of supports of the piping system. Piping systems supported by U-bolts fit into category III, and the damping constant for design of these systems without thermal insulation is 0.5%.

The main damping mechanism in piping systems supported by U-bolts is friction or collision occurring at the supports, which is same as piping systems supported by frame restraints. For this reason, piping systems supported by U-bolts are thought to be similar damping constants to systems supported by frame restraints, which are included in Category I.

Therefore the joint research was carried out involving 10 electrical utilities and 3 plant manufacturers from 2000 to 2001. Tests conducted in this research project subjected piping systems supported by U-bolts to vibration, with the aim of obtaining more appropriate values of the damping constant for design.

Details of the Research

Damping Mechanism

The damping mechanism for piping systems supported by U-bolts consists of damping due to piping material, damping due to fluid interaction, damping due to plastic deformation of piping and supports, and damping due to friction and collision between piping and supports (Table 2). It has been experimentally verified that of these, damping effects due to the piping material and the fluid interaction are minimal, and therefore they were excluded from this study. It is thought that the damping effects of plastic deformation of piping and supports are considerably large, but it was difficult to treat them for present design of actual piping systems. So they were also excluded from this study. Accordingly, this study focused on the damping due to friction and collision at the support structure.

The dispersion energy caused by the friction with axial pipe motion at U-bolt supports (the friction between piping and supporting frame) is thought to be same as that occurring at frame restraints. The damping mechanism of this type of the dispersion energy had been studied [2], and this study examined the damping mechanism of friction and collision accompanying with perpendicular motion to the axial direction.

Study Procedure

As previously mentioned, the damping due to friction and collision at U-bolt supported piping systems were the subject of this study. This study referred the past procedures and utilized the damping estimation method. The actual procedures used to determine the damping constant for U-bolt supported systems were as follows:

i) Element tests were performed and the damping mechanism at U-bolt support was examined, and the dispersion energy was simulated by estimation equation of dispersion energy.
ii) Piping model excitation tests were conducted to verify the above simulation even for piping system.
iii) Damping values derived from the damping estimation method based on the dispersion energy estimation equation formulated in i) were compared with the damping constants obtained from the piping model excitation tests, verifying the appropriateness of the damping estimation method.
iv) The damping estimation method verified in iii) was applied to actual piping systems supported by U-bolts, and their damping constants were calculated.
v) Damping constants for design were proposed on the basis of the results obtained in iv).

In this study, four types of U-bolt used in actual piping systems were taken into account. Two types of these have “mounts”, and one is a U-plate. Fig. 1 shows those configurations.

Element Test

An element test was conducted to clarify the mechanism of the damping due to friction and collision, and to formulate the dispersion energy.

Vibration of the piping system in which friction and collision occur is generally non-linear, but was treated as equivalent linear system in this study. For this reason, we need following two assumptions:

i) The influence of local non-linearity at the piping support, in which friction and collision occur, is not large for the entire piping system, and therefore vibration response of the piping system may be treated as a linear vibration system.
ii) Energy dissipation due to friction and collision at the piping supports may be treated as an equivalent linear damping element.

These assumptions were used to estimate the damping effect due to friction and collision, which was considered as the dominant damping mechanism in the piping systems supported by U-bolts.

Test Conditions

a. Element Test Model

As shown in Fig. 2, an element test model consists of a straight pipe, which has cantilever shape, supported by a U-bolt. Fig. 3 shows a photograph of the element test model. The natural frequency of it can be adjusted by changing the position of the U-bolt support or an additional weight attached at the free end of the model.

b. Test Method

Generally, on the tests to investigate damping characteristics of linear damping element, sinusoidal excitation is used. But friction and collision were expected to occur in the response of it, and vibration characteristics changes from moment to moment, random excitation was performed in the test.

Test parameters were as follows, which were considered to affect on the dispersion energy due to friction and collision:

- U-bolt type
- Natural frequency of the model
- Excitation Level
- Direction of excitation
- U-bolt upper clearance δ_V

Test Results

Element test results were as follows:

a. Dominant Frequency in Test Model

To obtain the dominant frequency, transfer function was calculated. It was found as the peak of the frequency response curve. The dominant frequency varied slightly with U-bolt type.

Fig. 4 shows frequency response curves of all models of which piping diameter, support position and additional weight were changed. The dominant frequencies of those were distributed from 5 to 25Hz, this frequency band is equivalent to the frequency range taken into consideration for seismic design of actual piping systems.

b. Load Displacement Characteristics

Fig. 5 shows an example of load displacement curve of A type U-bolt of δ_V = 1mm in a cycle when maximum response occurred. In the A type, which does not have a mount, the load displacement characteristics had partial load increase (sudden 'angular' load increase) caused by collision with a square loop due to friction.

Load displacement characteristics were obtained and dispersion energy calculated in the same way for U-bolt types B, C and D.

c. Dispersion energy In U-bolt Support

Dispersion energy for one cycle was calculated from the internal area of the load displacement curve. Fig. 6 shows the calculated dispersion energy ΔE.

B, C and D type U-bolts were put through the same procedure to calculate each dispersion energy.

Formulation of Dispersion Energy Estimation Equation

The calculated dispersion energy ΔE of each type of U-bolt had different tendency, and therefore dispersion energy estimation equations were formulated independently for each type of U-bolt.

Taking into consideration the type of each U-bolt, the dispersion energy for one cycle was simulated as the area of the load displacement curves of the friction and collision models. The equations for each type of U-bolt was divided into cases in which sliding did and did not occur, and the dispersion energy in the response level when sliding did not occur was calculated as 0. The following discussion gives details of the formulation of the dispersion energy equations for A type U-bolts.

a. Modeling Load Displacement Characteristics

U-bolt friction and collision behavior was modeled with friction, gap and spring elements in parallel combination, as shown in Fig. 7. A comparison with the modeled load displacement curve and test results is shown in Fig. 8. This figure shows that the modeled load displacement characteristics satisfactorily express the form of the load displacement curve obtained from the test result.

b. Formulation of The Dispersion Energy Estimation Equation

The dispersion energy estimation equation was formulated from the above-mentioned load displacement characteristics model.

$$i)\ F \le \mu N$$

$$\Delta E = 0$$

$$ii)\ F > \mu N$$

$$\Delta E = 4 \cdot \mu \cdot N \cdot \frac{\delta_H}{2} + 4 \cdot \mu \cdot N \cdot \frac{F - \mu \cdot N}{k_U}$$

μ : Coefficient of dynamic friction
δ_H : Horizontal clearance between piping and U-bolt (Sum of both sides)
F : Horizontal support reaction in piping support
N : Perpendicular support reaction
k_U : U-bolt rigidity

Fig. 9 shows a comparison between dispersion energy obtained from this equation and test results. This figure shows that the dispersion energy estimation equation satisfactorily expresses the tendency of $\Delta E/N$ to increase against $F\text{-}\mu N$ observed in test results.

Piping Model Excitation Tests

To verify the appropriateness of the damping estimation method using the U-bolt dispersion energy estimation equation, vibration tests were conducted on a full-scale test piece.

Test Piece and Support Conditions

As Fig. 10 shows, the test piece was a full-scale three-dimensional piping system of pipe diameter 100mm, featuring curved and branched sections. Fig. 11 shows the support conditions of the test piece. In the test piece horizontal pipes were supported by 3 U-bolts and vertical pipes were supported by 1 U-bolt. Tests were conducted using B type U-bolts, with an upper clearance of δ_V = 2mm between the U-bolt and the pipe.

Excitation Conditions

a. Input Waves

The earthquake response wave from the reactor containment inner concrete of the improved and standardized PWR 3 loop plant was utilized as the input earthquake wave for the vibration equipment.

b. Excitation Direction

Excitation Direction was horizontal-only and simultaneously horizontal and vertical. Horizontal-only excitation was used to find the damping constant for U-bolt supported piping systems. Simultaneous horizontal and vertical excitation was used to verify whether perpendicular support reaction during vertical excitation has any effect on the damping constant.

c. Level of Excitation

Three levels of excitation were used to find the dependence of piping system damping constants on vibration amplitude.

Test Results and Verification of Appropriateness of Damping Estimation Method

Fig. 12 shows a comparison with the relation of maximum pipe responsive displacement and damping constants from test results and damping constants calculated by the damping estimation method using the dispersion energy estimation equations.

Damping constants obtained from test results vary from 4.5%-18%. This shows that it is possible to estimate damping constants more conservatively by using the damping evaluation method.

Proposal of Damping Constants for Design of U-bolt Supported Piping Systems

Concept of Damping Constant for Design of U-bolt Supported Piping Systems

Damping constants for U-bolt supported piping systems in actual facilities are affected by the type and the number of U-bolts, piping route, vibration mode, etc., and therefore differ for individual piping systems. For this reason, in establishing damping constants for design, the damping estimation method was used to estimate the damping constants for multiple U-bolt supported piping systems in actual facilities and lower limits were chosen for these constants. This was the same method used to establish damping constants for design for the existing piping classifications I and II.

When utilizing the newly formulated dispersion energy estimation equation in the damping estimation method, damping constants were calculated assuming a uniform responsive displacement in each vibration mode, as in the formulation of the existing damping constants for design. The relationship between number of supports and damping constants was studied on this basis.

The stress due to inertial force (earthquake stress below) found when using the two types of damping constants listed below were then subjected to comparison, and a value for uniform responsive displacement for each vibration mode was considered.

i) Damping constants obtained from convergence calculations in a dependent relationship with responsive displacement for each mode (termed mode-damping constants below)

ii) Damping constants calculated after hypothesis of uniform responsive displacement in each mode (termed displacement hypothesis damping constants below)

i) represents the damping constants found from convergence in each mode. These values were used to calculate earthquake stress, which was compared to the earthquake stress calculated using the damping constants in ii) to achieve more accurate values. The earthquake stress found in i) was taken as a standard and compared with that found in ii) and the displacement occurring where the maximum values for both earthquake stresses converged was used as the displacement when calculating displacement hypothesis damping constants.

Establishment of Damping Constants for Design of U-bolt Supported Piping Systems

Damping estimations were conducted with uniform displacement in each vibration mode for the 28 U-bolt supported piping systems selected to establish the parameters for systems in actual use. A displacement of 2.5mm, the same used when the existing damping constants were established, was used to calculate the displacement hypothesis damping constants.

Fig. 13 shows the results of adjusting the estimated displacement hypothesis damping constants with reference to the number of supports. The lower limit for the estimated displacement hypothesis damping constant in U-bolt supported systems with four or more U-bolts in which the bolts are fixed to a supporting frame and take the full weight of the pipes (termed full pipe weight supporting U-bolts below) was 2.0%.

To find the hypothetically uniform responsive displacement values for each vibration mode, 5 U-bolt supported piping systems in which the damping constant approaches the lower limit were selected from among the U-bolt piping systems with 4 or more full pipe weight supporting U-bolts in the results of the above-mentioned displacement hypothesis damping constant estimations. These are the piping systems enclosed by the dotted line in Fig. 13. Earthquake stress values found from damping constants for each mode were compared with earthquake stress found from displacement hypothesis damping constants.

Fig. 14 shows that for a displacement of 2.5mm, the earthquake stress figures found from the displacement hypothesis damping constants were either the same as those found from the damping constants for each mode, or left a margin of safety. It is therefore appropriate to use the displacement hypothesis damping constants calculated for a displacement of 2.5mm as a basis in establishing damping constants for seismic design of U-bolt supported piping systems.

As Fig. 13 shows, in the case of piping systems supported by 4 or more U-bolts bearing the full weight of the pipes, the displacement hypothesis damping constants calculated for a displacement of 2.5mm are distributed with a lower limit of 2%. This is therefore an appropriate damping constant for seismic design of these piping systems.

CONCLUSIONS

Results of the study of damping constants for design of U-bolt supported piping systems are as follows:

i) Dispersion energy estimation equations for the 4 types of U-bolt used in actual facilities were formulated from load displacement characteristics obtained from element tests.

ii) These dispersion energy estimation equations were used in the damping estimation method to calculate estimated damping values, which were then compared with the damping constants obtained from full-scale piping model excitation tests. This was done to test the appropriateness of the damping estimation method using the dispersion energy evaluation equations. As a result, it was found that the estimated damping constants were conservative in relation to the damping constants obtained from tests, irrespective of responsive displacement. Obtaining damping constants using the damping estimation method was therefore judged appropriate from the perspective of conservative estimations of damping.

iii) The above-mentioned damping estimation method was used to calculate damping constants for U-bolt supported piping systems in actual facilities, and thereby establish damping constants for design. The lower limit for the calculated damping constant in piping systems with 4 or more full pipe weight supporting U-bolts was found to be 2.0%.

iv) The figure of 2.0% was judged to be an appropriate value for the damping constant for design of piping systems with 4 or more full pipe weight supporting U-bolts.

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[1]NUREG/CR-6241 Technical Guidelines for Aseismic Design of Nuclear Power Plants, Translation of JEAG 4601-1987, Brookhaven National Laboratory

[2]H. Shibata, et al., “A Damping characteristics of piping systems in nuclear power plants,” ASME PVP-Vol.73, 1983, pp151-178

Table.1 Damping constants for design of piping system

Piping type		Damping constant for design(%) With thermal insulation	Damping constant for design(%) Without thermal insulation
Ⅰ	Piping system supported mainly by snubbers and frame restraints, with four or more supports (snubbers or frame restraints)	2.5	2.0
Ⅱ	Piping system having snubbers, frame restraints, rod restraints, hangers, etc., with four or more supports (excluding anchors and U-bolts); not belong to piping Type Ⅰ	1.5	1.0
Ⅲ	Not belong to piping Type Ⅰ or Ⅱ	1.0	0.5

Table.2 Damping mechanism of piping systems supported by U-bolts

Damping mechanism	Degree of damping	Subject of this study
Damping due to piping materials	Minimal	No
Damping due to fluid interaction	Minimal	No
Damping due to plastic deformation of piping and supports	Large	*No
Damping due to friction or collision between piping and supports	Large	Yes

* Experimental study of this factor is difficult, and therefore it was excluded from this study.

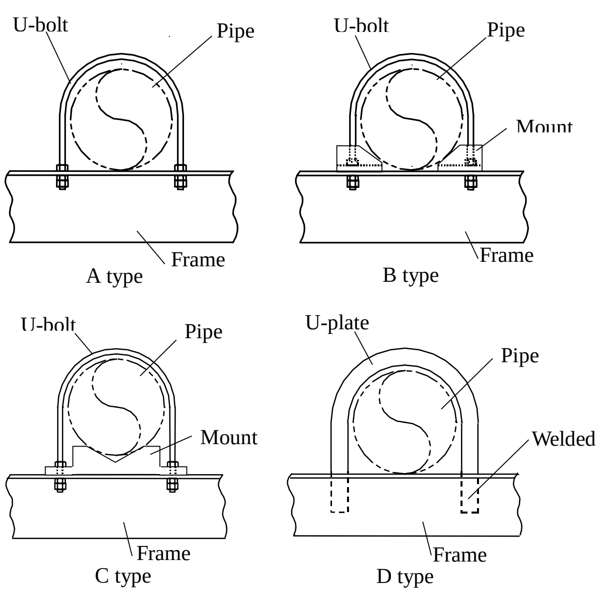


Fig.1 U-bolt types forming the subjetcs of this study

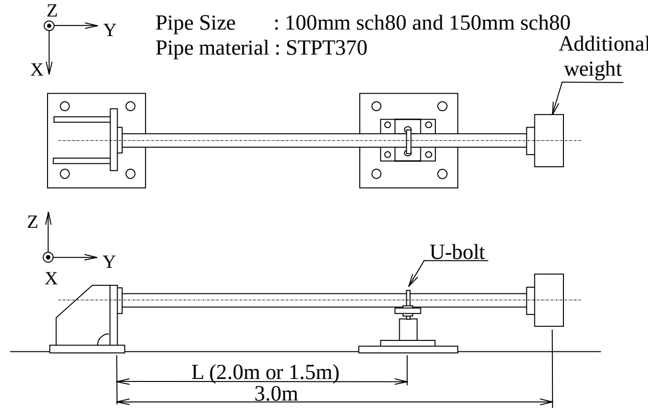


Fig.2 U-bolt element test model Test piece

Fig.3 Photograph of U-bolt element test model

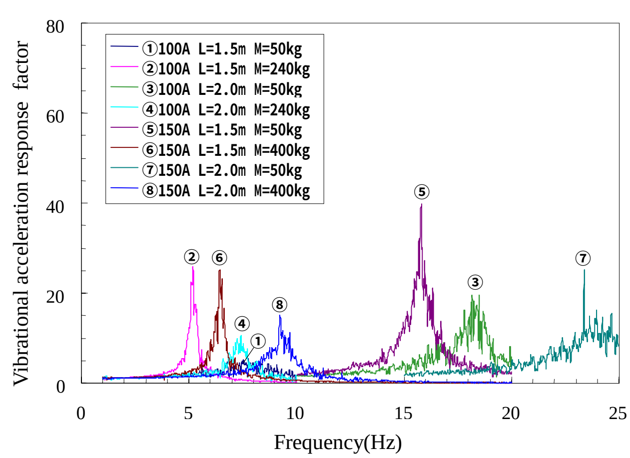


Fig.4 Changes in frequency due to support position and mass of attached weight (A type)

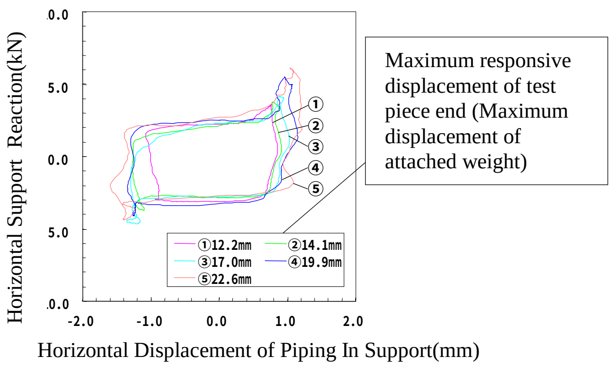
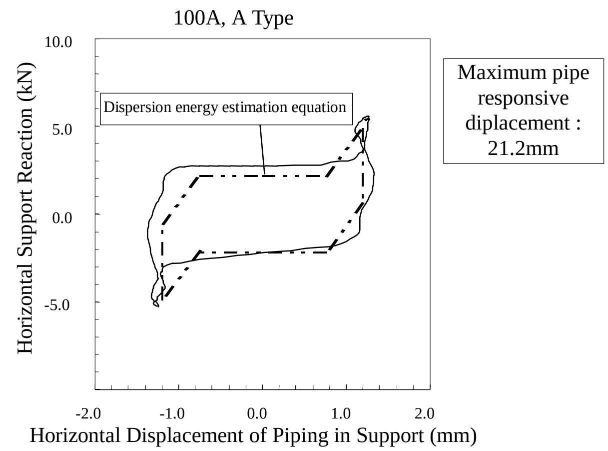


Fig.5 Load displacement characteristics
(U-bolt element test results)



(M=240kg, L=1.5m, δ_V =2mm, dispersion energy estimation equation parameters: δ_H =1.5mm, μ =0.45, k_U =6kN/mm)

Fig. 8 Comparison with load displacement curves obtained from dispersion energy estimation equations and test results

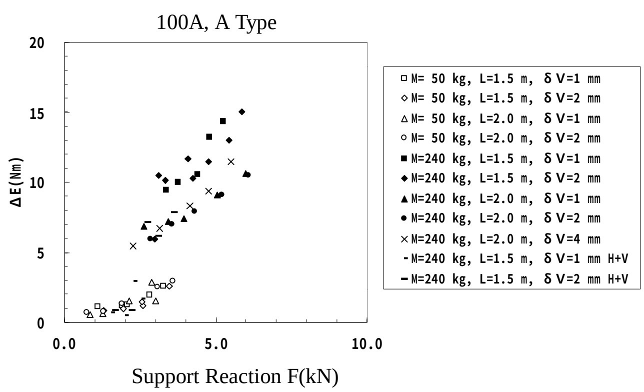


Fig.6 Relationship between support reaction and dispersion energy (U-bolt element test results)

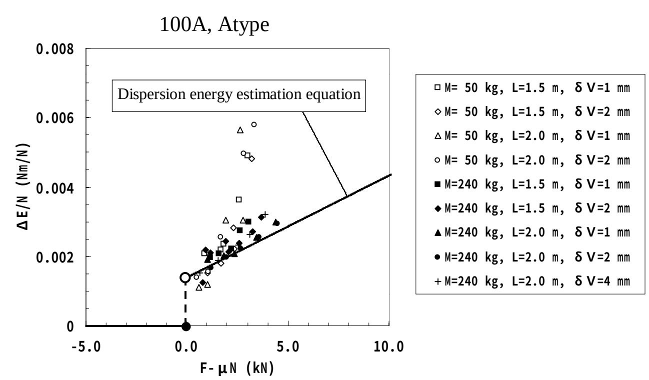
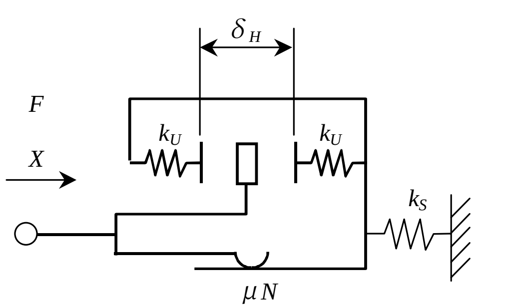


Fig. 9 Comparison between dispersion energy obtained from dispersion energy estimation equation and test results



δ_H : Mass of horizontal clearance (Sum of both sides)
k_U : U-bolt rigidity
k_S : Frame rigidity (Considered as sufficient rigidity)
μN : Frictional force

Fig. 7 U-bolt friction and collision model

Fig. 10 Photograph of full-scale piping model excitation test

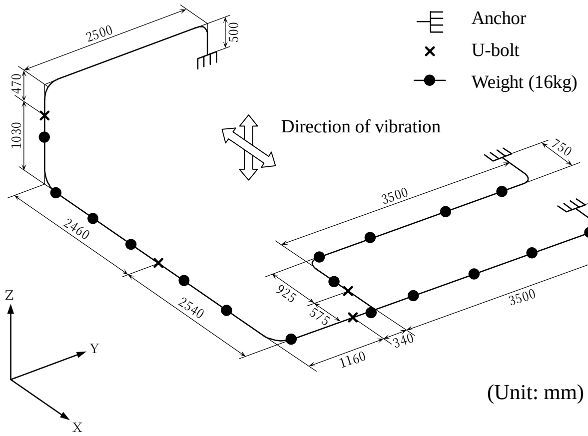


Fig. 11 Test piece support conditions

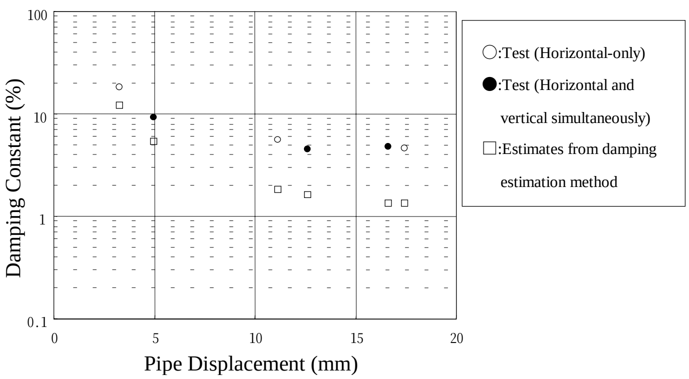


Fig. 12 Comparison between damping constants from test results and calculated from damping estimation method

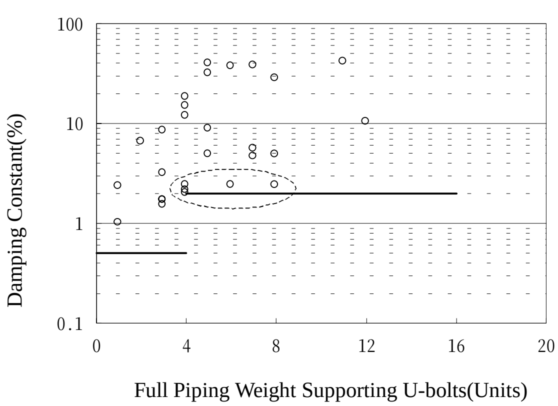
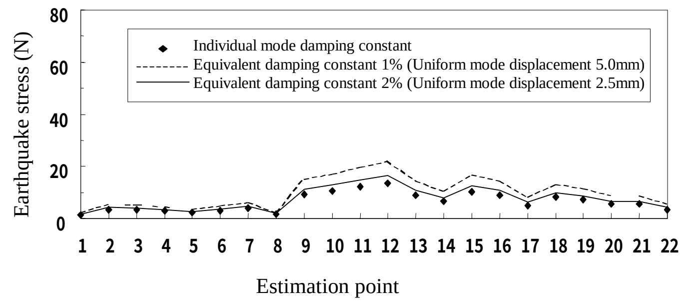


Fig. 13 Damping estimation results for U-bolt supported piping systems (displacement 2.5mm)



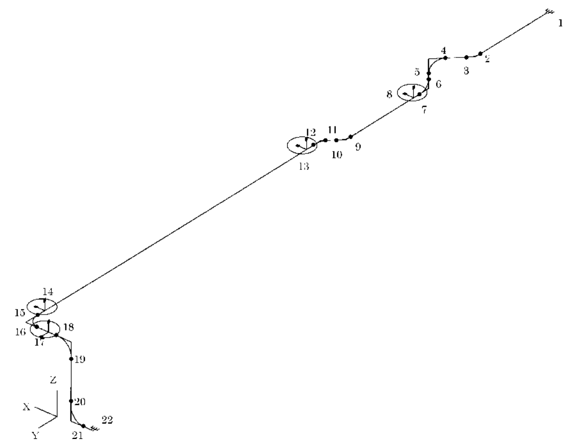


Fig. 14 Comparison with earthquake stress found from displacement hypothesis damping constants and individual mode damping constants

