Seismic Design of Piping Systems in Nuclear Facilities

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SUMMARY

This paper presents a new approach for simplifying the seismic design of piping systems installed in nuclear facilities. In aseismic design for piping systems, it is the most popular and convenient way to compute the maximum support spacing which makes piping system rigid enough. In this general practice, however, the calculated stresses of pipes due to design earthquakes are usually much smaller than allowable stresses. This is so because more supports, in general, must be installed to make a piping system rigid than those required to carry seismic load, and this causes the increase in the cost of installation work of piping systems in nuclear facilities.

In this paper, the authors describe a simplified approach to determine the pipe-support spacing which is not frequency controlled but stress controlled one with consideration of the relationship between dynamic properties of a building and piping systems.

This method utilizes an "allowable static load curve" and a floor response spectrum curve to obtain an allowable static load and a corresponding required eigenperiod of a piping system from an intersection of two curves. The maximum support spacing of pipe and the eigenperiod of support can be calculated easily from the allowable static load and the required eigenperiod. This allowable static load curve is developed for a variety of pipe geometries, configurations and stresses available to carry seismic and dead weight loads as a function of eigenperiod of a pipe-support system which is idealized as a two degree-of-freedum model. Here the allowable static load can be defined as the static load which induces the maximum stress of the same value with the stress available to carry seismic and dead weight loads in a pipe with a certain geometry, configuration and eigenperiod of pipe-support system.

1. INTRODUCTION

In a simplified seismic design for piping systems installed in nuclear facilities, the maximum pipe-support spacing method is generally used to make the whole systems rigid and move with a building structure without any significant amplification during an earthquake. Also, Stevenson and Bergman had presented papers [1] [2] proposing a new simplified method to obtained the stress controlled maximum pipe-support spacing considering an allowable stress limit and a peak of an acceleration response spectrum adjusted by a rectifying factor.

This paper presents a new simplified approach of the pipe-support spacing considering the allowable stress limit and the seismic load obtained from the relationship between the acceleration response spectrum and the dynamic properties of the piping system including support structure.

2. GENERAL METHOD

As described in INTRODUCTION, two simplified methods are used as general practice in order to determine pipe-support spacing.

One is the method to calculate such support spacing as to make pipe rigid enogh to avoid any amplifications of acceleration during earthquakes. This method is very simple and maybe the most popular one. In this method, however, the generating stresses in pipe due to an earthquake generally have too much redundancy against the allowable stress limit. Also, it is necessary to make the support structure so stiff that its vibrational effect on the dynamic propereties of pipe can be neglected.

The othe one is proposed by Stevenson and Bergman. This is the method to calculate such support spacing as that the generating stress in pipe is approximately the same with the allowable stress limit considering the acceleration response spectrum. The merit of this method is that much more economical support spacing with reasonable redundancy can be obtained and also that the seismic load can be estimated very easily from the peak of an acceleration response spectrum adjusted by rectifying factor.

3. PROPOSED METHOD

3.1 CONCEPT

The seismic load working on a piping system is fixed by a floor response spectrum and dynamic properties of the system. And it is very difficult to estimate the appropriate seismic load from the peak response spectrum value.

In this proposed method, the seismic load is obtained taking account of the relationship between the acceleration response spectrum and the dynamic properties of piping system.

The floor response spectrum value which corresponds to the seismic load generating a maximum stress equal to the allowable stress limit in a piping system with a certain fundamental eigenperiod is calculated in advance. If an actual floor response spectrum value is smaller than the critical value described above, the actual generating stress is always smaller than the allowable stress limit.

Here, this critical value is defined as "allowable static load" and presented as an "allowable static load curve".

The intersection of the allowable static load curve and the actual floor response curve drawn on the same graph gives the maximum allowable static load of a certain piping system and the maximum allowable eigenperiod of the system.

From this eigenperiod, the maximum allowable pipe-suppot spacing can be obtained very easily.

3.2 ALLOWABLE STATIC LOAD CURVE

The maximum bending moments in pipe due to seismic load and dead weight load are expressed as follows;

$$Mb = A \cdot Cd \cdot w \cdot L^2 \qquad (1)$$

$$Ma = Cs \cdot w \cdot L^2 \qquad (2)$$

where
- Mb : maximum bending moment due to seismic load, kg-cm
- Ma : maximum bending moment due to dead weight load, kg-cm
- A : seismic coefficient ($\ddot{a}/g$)
- $\ddot{a}$: seismic load, cm/sec^2
- g : acceleration of gravity, 980 cm/sec^2
- Cd : coefficient of bending moment due to seismic load
- Cs : coefficient of bending moment due to dead weight load
- w : weight per unit length, kg/cm
- L : pipe-support spacing, cm

Here, L^2 is expressed as;

$$L^2 = \frac{\lambda^2}{2\pi Fp}\sqrt{\frac{E \cdot I \cdot g}{w}} \qquad (3)$$

where
- λ : nondimensional coefficient defined from boundary condition and mode shape
- Fp : the first natural frequency of pipe ($\frac{1}{2\pi}\sqrt{\frac{Kp}{Mp}}$)
- Mp : equivalent mass of pipe, $kg \cdot sec^2/cm$
- Kp : equivalent spring coefficient of pipe, kg/cm
- E : modulus of elasticity, kg/cm^2
- I : moment of inertia of pipe, cm^4

The stress limit for ASME Section III-NC Class 2 piping [3] is

$$\frac{Pmax \cdot Do}{4 \cdot Tn} + 0.75 \cdot i \cdot \frac{Ma + Mb}{Z} \leqq 1.2\ Sh \qquad (4)$$

From Eq.(1),(2),(3) and (4);

$$\frac{Pmax \cdot Do}{4 \cdot Tn} + 0.75 \cdot i \frac{Do\ \lambda^2}{4\pi \cdot Fp} (Cs + A \cdot Cd)\sqrt{\frac{E \cdot w \cdot g}{I}} \leqq 1.2\ Sh \qquad (5)$$

where
- Sh : basic material allowable stress range at maximum heat temperature as defined by code, kg/cm^2
- Pmax: peak pressure resulting from pressure transient except it can be considered equal to P unless the pressure transient is considered concurrentry with earthquake, kg/cm^2
- Do : outside diameter of pipe, cm
- Tn : nomimal wall thickness of component, cm
- Z : section modulus of pipe, cm^3
- i : stress intensification factor

Idealizing a pipe-support system as a two degree-of-freedum model as shown in Fig.1, the first frequency of pipe is written as;

$$Fp = Fo\sqrt{\frac{(Fs/Fo)^2 - 1}{(Fs/Fo)^2 - 1 - \mu^2}} = Fo \cdot C \tag{6}$$

where Fo : the first natural frequency of a two degree-of-freedum model, Hz

Fs : the first natural frequency of support $(\frac{1}{2\pi}\sqrt{\frac{Ks}{Ms}})$

Ms : equivalent mass of support, $kg \cdot sec^2/cm$

Ks : equivalent spring coefficient of support, kg/cm

μ^2 : mass ratio of pipe to support (Mp/Ms)

C : $\sqrt{\frac{(Fs/Fo)^2 - 1}{(Fs/Fo)^2 - 1 - \mu^2}}$

On the other hand, the participation functions Ui at the point of a pipe is written as;

$$Ui = \frac{(Fs/Fi)^2}{\{(Fs/Fi)^2 - 1\}^2 + \mu^2} \tag{7}$$

where Fi : the i-th natural frequency of a two degree-of-freedum model

It is necessary to consider the first and second participation functions to obtained a seismic load in pipe.

The seismic coefficient is

$$A = \sqrt{(U1 \cdot \ddot{a}1)^2 + (U2 \cdot \ddot{a}2)^2} \;/\; g \tag{8}$$

where U1 : the first participation function at a point of Mp

U2 : the second participation function at a point of Mp

$\ddot{a}1$: acceleration response at the first eigenperiod, cm/sec^2

$\ddot{a}2$: acceleration response at the second eigenperiod, cm/sec^2

Hence, assuming that $\ddot{a}2$ is equal $\ddot{a}1$ in order to simplify Eq.(8), the seismic coefficient A can be rewritten as;

$$A = \sqrt{U1^2 + U2^2} \cdot \ddot{a}1 \;/\; g = U \cdot \alpha \tag{9}$$

where U : $\sqrt{U1^2 + U2^2}$

α : allowable static load

Substituting Eqs.(6),(7) and (9) into Eq.(5),

$$\frac{Pmax \cdot Do}{4 \cdot Tn} + \frac{0.75 \cdot i \cdot \lambda^2}{4\pi} Do\sqrt{\frac{E \cdot w \cdot g}{I}} \frac{1}{Fo}\left(\frac{Cs}{C} + \frac{Cd \cdot U \cdot \alpha}{C}\right) \leqq 1.2\ Sh \tag{10}$$

From Eq.(9),

$$\alpha \leqq \frac{1}{Cd} \frac{[(Fs/Fo)^2 - 1]^2 + \mu^2}{(Fs/Fo)^2} \left\{ \frac{4\pi\,[1.2\ Sh - (Pmax \cdot Do/4Tn)]}{0.75 \cdot i \cdot \lambda^2\ Do\sqrt{\frac{E \cdot w \cdot g}{I}}} Fo - Cs \right\} \tag{11}$$

Using Eq.(11), the allowable static load can be calculated.

Hence, the allowable static load takes minimum value when U/C is maximum value. Fig.3 shows the relationship between Fs/Fo and U/C.

3.3 EXAMPLE

The example calculation is performed concerning a straight piping system with nominal sizes of 1B,4B and 10B.

The assumption was made as follows;

Material : SUS 304L
Schedule No. : 40
Allowable stress Sh : 2100 kg/cm^2
Stress intensification factor : 1
Vibration model : see Fig.2
Coefficient Cd : 1/8 (see Fig.2)
Coefficient Cs : 1/24 (see FIg.2)
Mass ratio Mp/Ms : assuming 0.2
coefficient U/C : 1.65 from Fig.3

Under these conditions, the allowable static load curve can be shown as Fig.4 together with a floor response spectrum.

Table.1 shows the calculated allowable pipe-support spacing and the pipe-support spacing with the natural frequency of 32 Hz.

4. CONCLUSIONS

From the example calculation described above, it is concluded that;

(1) In this method, the obtained pipe-support spacing is longer than by general simplified methods. Here, in order to determine the pipe-support spacing using this method, it is necessary to consider an allowable buckling length,too.

(2) The allowable static load, that is, the resistance of piping system against seismic load increases in accordance with decrease of the fundamental eigen-period of the pipe-support system.

In this study, the effect of the second mode is not evaluated properly to estimate the seismic load in pipe. This is subjected which is necessary to be investigated in future.

Also, further study is necessary with regard to a vareity of configuration of piping system including bend, branch, lumped mass and so forth to apply this method in the practical piping system design.

5. REFERENCES

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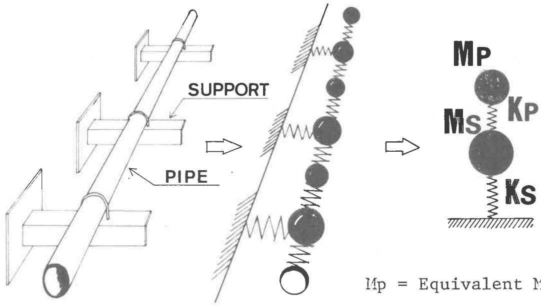

Mp = Equivalent Mass of Pipe

Ms = Equivalent Mass of Support

Kp = Equivalent Spring Coefficient of Pipe

Ks = Equivalent Spring Coefficient of Support

Fig. 1 Model Scheme of the Pipe-Support System of Two Degree-of-Freedom

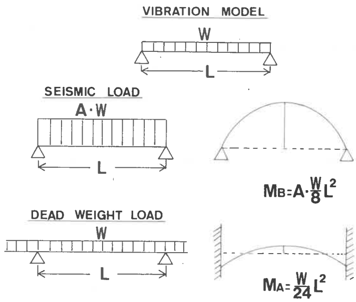

Fig. 2 Loading Conditions of the Pipe-Support Spacing

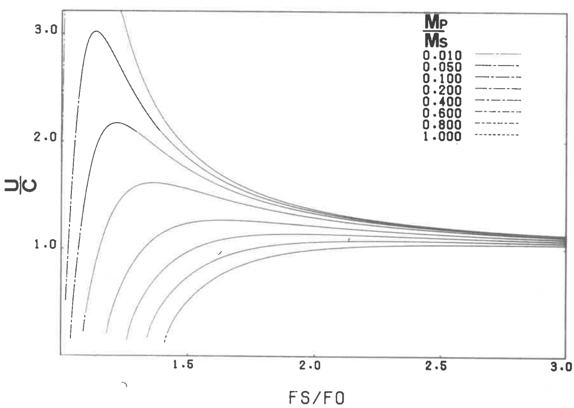

Fig. 3 The Relation between Fs/Fo and U/C

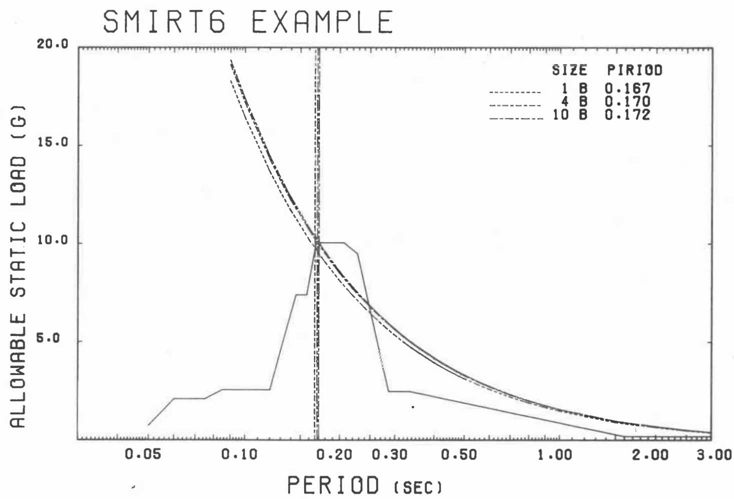

Fig. 4 The Allowable Static Load Curve

Table.1 Calculated Result of the Allowable Pipe-Support Spacing

(CM)

NO.	SEC	1 B	4 B	10 B
	0.031	164.34	308.71	476.18
1	0.050	221.60	416.27	642.07
2	0.060	242.75	456.00	703.36
3	0.070	262.20	492.54	759.71
4	0.080	280.31	526.54	812.17
5	0.090	297.31	558.48	861.43
6	0.100	313.39	588.69	908.03
7	0.120	343.30	644.88	994.70
8	0.140	370.81	696.55	1074.40
9	0.160	396.41	744.65	1148.58
10	0.180	420.46	789.82	1218.25
11	0.200	443.20	832.54	1284.15
12	0.220	464.84	873.18	1346.83
13	0.240	485.50	912.00	1406.71
14	0.260	505.33	949.24	1464.16
15	0.280	524.41	985.07	1519.43
16	0.300	542.81	1019.65	1572.75
17	0.320	560.61	1053.09	1624.33
18	0.340	577.87	1085.50	1674.33
19	0.360	594.62	1116.97	1722.87
20	0.380	610.91	1147.58	1770.08
21	0.400	626.78	1177.39	1816.06
22	0.420	642.26	1206.47	1860.91
23	0.440	657.38	1234.86	1904.70
24	0.460	672.15	1262.61	1947.51
25	0.480	686.61	1289.77	1989.39
26	0.500	700.77	1316.36	2030.42
27	0.550	734.97	1380.61	2129.52
28	0.600	767.65	1442.00	2224.21
29	0.700	829.16	1557.54	2402.42
30	0.800	886.41	1665.08	2568.30
31	0.900	940.18	1766.08	2724.09
32	1.000	991.03	1861.62	2871.44
33	1.500	1213.76	2280.00	3516.79
34	2.000	1401.53	2632.72	4060.84
35	2.500	1566.96	2943.47	4540.15
36	3.000	1716.52	3224.41	4973.49