SMiRT-12 / K. Kussmaul (Editor)

K18/4

SEISMIC RESPONSE AND RESISTANCE OF SMALL BORE PIPES

R. Masopust and J.D. Stevenson

Stevenson and Associates, Pilsen & Cleveland

1. Introduction

This paper presents an analysis of seismic response and seismic resistance of 90 representative pipe segments with a diameter up to 100 mm and with different (from 3 to 7) Lateral to Vertical Support Span Ratios (LVSSR) based on the maximum Dead Weight (DW) span as suggested by Table NF-3611-1 of ASME BPVC Section III [1]. This analysis has been performed for three levels of earthquake with ZPGA equal to 0.3, 0.2 and 0.1 g. The main aims of this work are:

- to show, that seismic resistance of such pipe systems is essentially governed by their displacements, and by support reactions, rather than by traditional pipe stress criteria,
- to show typical limiting stresses, displacements and support reactions depending on the pipe LVSSR,
- to create on this basis the recommended limiting spacing tables giving the maximum LVSSR for such pipes,
- to calculate numerical values of the factor K_1 for the Load Coefficient Method-Simplified (LCM-S) [2] as an equivalent static load based on the applicable response spectrum,
- to compare the maximum stresses and displacements of pipe segments obtained by the Response Spectrum Modal Analysis Method (RSMAM) to those which result from the equivalent static solutions by the Load Coefficient Method (LCM) [2], by the Load Coefficient Method-Simplified (LCM-S) using the determined K_1 factors, and by the Equivalent Static Analysis Method (ESAM) as defined in the U.S. NRC SRP 3.7.2 [3] with the equivalent static load coefficient taken equal to 1.5 times the peak of the applicable response spectrum.

2. Pipe Segments

Straight, horizontal single and double bent, T and U - shaped, vertical double bent, space double and triple bent pipe segments [6] have been analysed assuming that they are:

- cold od slightly warm ($T_D \le 90^oC$), with and without a light insulation (up to 10% of the pipe self weight)
- with and without a low internal pressure (up to 5 MPa),
- with a nominal diameter up to 100 mm,
- material SA 106 Grade B or similar with the basic yield limit about 240 MPa or higher,
- schedule from 40 to 80, i.e. with a ratio of the wall thickness to the nominal diameter from 0.05 to 0.1,
- class 2 or 3 designed to ASME (under some circumstances applicable also for class 1),
- service level C or D in accordance with the ASME BPVC, Section III, and filled with water.

In-line pipe valves may be located at supports restrained in all directions, or they are assumed to be replaced by an equivalent pipe length. Connections and fittings are assumed as follows:

- pipe segments of diameter up to 50 mm with socket welding connections and fittings,
- pipe segments of diameter from 50 mm to 100 mm with butt welding straight pipe elements, tees, and elbows with two different radiuses 1.5 times and 4 times pipe diameter.

It was also assumed that the socket welds may be placed anywhere along the pipe and that the tees and elbows may be shifted to the point of maximum segment response moments, the exact positions of which vary within each pipe segment group and depend on the pipe LVSSRs. Calculations show that these tees and elbows are in the analyzed pipe segments located near such points, but usually not exactly at them. On the other hand, experience shows that the resultant pipe stress is strongly dependent not only on the value of the primary stress indice, but also on the point of the pipe in which this indice is applied. This means that a good engineering judgement is to assume that tees and elbows may be slightly shifted to the points of the maximum pipe response moments. Therefore, the primary bending stress indice B_2 associated with elbows and tees is applied not only at these locations, but also at nodes of straight pipe elements at points of the maximum resultant moment loading on the pipe cross section. The DW span is equal to 3.05 m for pipe segments of 50 mm diameter, and 4.27 m for segments of 100 mm diameter. The DW span is measured along the pipe length. Vertical and horizontal force-type support restraints of the pipe segments are assumed to be rigid which means that their actual stiffnesses could not affect the dominant frequencies of the pipe seismic response. Such simple support conditions are typical for the majority of pipe segments which compose realistic space multi-span small bore pipe systems.

3. Methods of Analysis

a) RSMAM

The applied floor response spectra are shown in Fig. 1. Above 2 Hz the reference elastic response spectra developed by SSRAP for the SQUG A-46 program which are applicable up to 12 m above grade [4], and the R.G. 1.60 spectra below 2 Hz, with three different ZPA = 0.45, 0.3, and 0.15 g which approximately represent a plant on soil with ZPGA = 0.3, 0.2, and 0.1 g respectively. They are characteristic for structures subjected to the soil-structure interaction and they have been applied the same in three directions (two of them are horizontal and one is vertical). It should be also noted that the spectrum shape remains the same for all three ZPGA levels.

b) LCM-S

This method is used in general accordance with the proposed ASME Code Changes [2] (the new N-1213(a)) which is consistent with the ASME Code Case N-468 except that: (a) the K_1 factors are determined on the basis of seismic inertia induced moment stresses rather than resultant moments in the pipe, and (b) the K_1 factors are determined from the values of peak stresses in each segment rather than from the mean values of the maximum seismic moment stresses within the 25% of the largest stress. This modified definition of the factor K_1 is used to permit the evaluation of pipe segments containing different diameters and schedules. In pipe systems of the same schedule and diameter it makes no difference if seismic inertia induced moments or stresses are used. However, in the more general case of pipe systems which contain different schedules or diameters it would be necessary to use stresses rather than moments for comparison purposes. Also the K_1 factor determined by comparing the peak values of maximum seismic moment stresses in each piping segment instead the mean values of the maximum seismic moment stresses within 25% of the largest stress are used. In making this change it was recognized that the difference between K_1 factors determined by either of these procedures is small when a large number of pipe segments are considered.

The real seismic behaviour of pipes, which can vary from quite stiff to very flexible is more complicated in comparison to most other mechanical components which where properly anchored are typicallly relatively rigid (f_f > 8.0 Hz). Due to a great variety of pipe seismic responses, the K_1 factors may vary significantly as a function of frequency characteristics, from 0.7 to 4.7 for analyzed pipe segments. The problem is how to divide all pipe segments into several groups within which the variation of the K_1 factor would be acceptably narrow for practical applications. It was recognized that the governing parameters of all pipe segments are their LVSSRs which mostly predetermine the pipe frequency characteristics. The pipe segments of groups A through H with the same LVSSRs have almost the same or very similar fundamental natural frequencies independent of their geometry. However, even within each group with the same LVSSR, the variation of the K_1 factor still remains relatively large. Therefore, the values of the K_1 factors recommended for practical applications are slightly higher that the mean values determined within each pipe segment group. It should also be understood that the computation of K_1 factors by comparison to RSMAM is in itself a conservative estimate of seismic response. The following parameters have been applied to determine static forces equivalent to seismic inertia effects with the LCM-S method:

$$F_{pi} = K\,A\,W \tag{1}$$

where
F_{pi} = the equivalent static force applied to the component in the ith direction,
K = $d_m\,K_1$,
K_1 = a factor which accounts for the shape of the applicable seismic design ground and amplification of floor response spectra used on generic or site specific basis. This factor K_1 on a site specific basis shall be chosen such that the peak values of the pipe seismic inertia induced moment stresses using LCM-S are equal to those determined from RSMAM. For generic applications the K_1 factor may be taken equal to 6.5 for piping supported at one half or less of the height of the supporting structure. To adjust for other building height locations the generic 6.5 factor may be modified by the relationship $K_1 = 3.7\,[1.5 + 1.0\,(H_x/H_n)]$ for plants on soil, where H_x is the applicable height above the base and H_n is the total height of the building structure. For plants on rock the generic K_1 factor would be determined as $K_1 = 3.7\,[1.0 + 1.5\,(H_x/H_n)]$,
A = the zero period ground acceleration defined for the site and expressed in percent of g.
d_m = 1.2 for pipe moment stresses and displacements, and 1.0 for support reactions.
W = the total dead load including normal operation live loads.

c) LCM

The following parameters have been applied with the LCM method [5]:

$$F = A\,R\,A_c\,A_{xh}\,A_{xv}\,W \tag{2}$$

where
A = the same as in (1),
R = 1.5 (more than 2 supports),
$A_{xh} = 1.0 + 0.15\,(h_{xh}/h_{nh}) = 1.15$, (here $h_{xh}/h_{nh} = 1.0$, therefore the structure is assumed to be symmetric),
$A_{xv} = 1.5 + 1.0\,(h_{xv}/h_{nv}) = 1.5 + 1.0\,(10/50) = 1.7$ (assuming SSI site with piping supported 10 m above the base mat in a 50 m high building), A_c as given in Ref. [5,6], with

$A_c = K_1'K_2\,/(\beta_b + \beta_e) = 0.75 \times 0.25/(0.07 + 0.05) = 1.5625$
($K_1' = 0.75$, $K_2 = 0.25$, $\beta_b = 0.07$, $\beta_e = 0.05$ and $f_b = 2.5$ Hz)

d) ESAM

This method has been used as defined in the U.S. NRC SRP 3.7.2 [3] with the uniform static load coefficient taken equal to 1.5 times the peak of the applicable response spectrum.

4. Results of Analysis

Complete results of the DW (static) + seismic (RSMAM) analysis, i.e. the maximum pipe moment stresses, pipe displacements, and horizontal and vertical support reactions are shown in Ref. [6]. Recommended maximum LVSSRs have been extracted from these results and they are shown for three levels of earthquake (ZPGA = 0.3, 0.2, and 0.1 g) and for Service Level D according to the ASME BPVC Section III requirements in Tables 1 and 2. The seismic resistance of the pipe segment to inertia loads is assured according to the different allowable stress and horizontal displacement criteria if the actual or design LVSSRs are equal or lower than the recommended values. They may be used, at least, for the preliminary design or layout of such pipes and for evaluation of their seismic margins in operating NPPs. The following formulas have also been extracted from the results of the RSMAM analysis for approximate evaluation of DW + seismic pipe support reactions:

(a) vertical direction
$R_{vert} = 1.3\,w\,L\,(1 + 2\,ZPGA/g)$ (for supports on horizontal runs) (3)
$R_{vert} = 2.5\,w\,L\,(1 + 6\,ZPGA/g)$ (for supports on vertical runs) (4)

(b) horizontal direction
$R_{hor} = 10\,w\,(LVSSR)^{0.5}\,L\,ZPGA/g$ (in lateral direction) (5)
$R_{hor} = 1.2\,n\,w\,L\,ZPGA/g$ (in axial direction) (6)

where

w = the weight of the pipe including the fluid inside the pipe (per length unit),

L = the vertical (DW) support span,

n = the number of DW spans which are restrained by the support in the axial (longitudinal) direction,

or nL = the total length of the pipe segment which is axially restrained by the support.

DW and seismic inertia effects of valves and similar devices located at supports, if any, should be added to the pipe support reactions determined by these formulas. When one of the pipe ends is attached to an equipment nozzle or to a pipe penetration, the maximum resultant moments at these nodes may be estimated as

$$M = \alpha\ w\ L^2\ ZPGA/g \tag{7}$$

where all items have the same sense as above, and α = 5.0, 6.0, 7.0, 8.0, and 8.0 for LVSSR = 3, 4, 5, 6, and 7 respectively. Such estimated moments should be applied to the weakest nozzle cross sectional axis.

How do standard pipe support stiffnesses (non-rigid) affect maximum moment stresses, maximum displacements and support reactions determined by RSMAM? This problem is important for general piping system seismic evaluations because non-rigid support stiffnesses may change fundamental natural frequencies of the piping system towards higher response spectral accelerations and hence larger stresses in the pipe and larger reaction loads. However, the practical cases analyzed here have been shown for LVSSR greater than 3 to have relatively flexible pipe segments with fundamental natural frequencies essentially below 1.25 Hz (i.e. below the resonant region as defined in Figure 1). For piping systems in the resonant region with LVSSR of 3 or less the actual pipe support stiffnesses cannot increase the seismic response characteristics. For LVSSR greater than 3 the systems are already out of resonance and any support flexibility will move the piping system further away from the resonant region. For LVSSR 3 or less resonance is assumed so seismic inertia stresses and reactions are maximized.

The following K_1 factors have been extracted from the results and may be recommended for general application of LCM-S in seismic analysis of piping systems: K_1 = 4.0, 2.4, 1.9, 1.6 and 1.3 for LVSSR = 3, 4, 5, 6 and 7 respectively. These K_1 factors provide as a minimum an additional 10% margin in comparison to the average values of K_1 factors. As an additional conservative simplification, a K_1 factor of 4.0 could be applied to piping systems in potential resonance with LVSSR of 3 or less. For piping systems with LVSSR of more than 3, a K_1 factor of 2.4 could be used. This would eliminate any underestimation of LCM-S as compared to RSMAM.

As shown in Ref. [6] and also in Fig. 2, ESAM with the static load coefficient equal to 1.5 times the peak of the floor spectrum gives generally much higher maximum values of moment stresses, displacements and support reactions. Differences between values determined by ESAM and RSMAM are greater for larger LVSSRs. Therefore, ESAM is a much more conservative method than RSMAM, and becomes significantly more conservative when LVSSR increases which typically occurs at lower seismic hazard sites.

5. Conclusions

The recommended maximum LVSSRs, illustrated in Tables 1 and 2, have been extracted from the results of DW + seismic RSMAM analyses of 90 representative small bore pipe segments. They are recommended for approximate seismic evaluations of realistic pipe systems under the conditions described above. A simple example demonstrating how to use these seismic spacing tables is done in Ref. [6]. Seismic resistance of such piping systems is essentially governed by their displacements, seismic interactions, or by support reactions, rather than by traditional stress criteria in the piping. Formulas (3) to (7) are recommended for evaluation of maximum support reactions and maximum resultant moments at places in which the pipe is attached to the more rigid component nozzles.

Numerical values of the K_1 factors which depend on LVSSR have been developed on the same basis as the seismic spacing tables and are recommended for general applications of LCM-S in seismic analysis of small bore pipings. Maximum moment stresses, horizontal displacements and also maximum support reactions determined by LCM-S using these K_1 factors are slightly conservative in comparison to those determined by RSMAM and are not sensitive to the actual support stiffnesses. Therefore, the actual support stiffnesses should no longer be a design parameter when using LCM-S with these recommended K_1 factors and there is no requirement to specifying that supports be rigid.

Results obtained from the seismic analysis of 90 different pipe segments by four methods, RSMAM, LCM-S, LCM, and ESAM, have been compared. Good correlations between the results determined by RSMAM and LCM-S which are illustrated in Ref. [6] may be important for more practical design of safety related pipings in future.

REFERENCES

/1/ ASME Boiler and Pressure Vessel Code, Section III. ASME, 1989.

/2/ Proposed Changes to Appendix N-1210 to ASME BPVC, Section III, the new N-1213(a) and N-1213(b). Stevenson and Assoc., Cleveland,1991.

/3/ Standard Review Plan for the Review of Safety Analysis Reports for Nuclear Power Plants. Report NUREG-0800. U.S. NRC, Washington, 1989.

/4/ Use of Seismic Experience and Test Data to Show Ruggedness of Equipment in Nuclear Power Plants. Prepared for SQUG by SSRAP. 1988.

/5/ Stevenson, J.D., Application of Simplified Seismic Analysis Methods to Nuclear Power Plants. Final Proceedings of the 3rd Symposium "Current Issues Related to Nuclear Power Plant Structures, Equipment and Piping", Orlando, Florida, December 1990. Publ. by North Carolina State University, Raleigh, 1991.

/6/ Masopust, R. and Stevenson, J.D., Development of Static Coefficient for Use Seismic Evaluation of Nuclear Safety Related Pipe Systems and Seismic Spacing Tables for Small Bore Pipes. Stevenson and Associates, Cleveland, 1992.

Fig. 1 Applied Floor Response Spectra

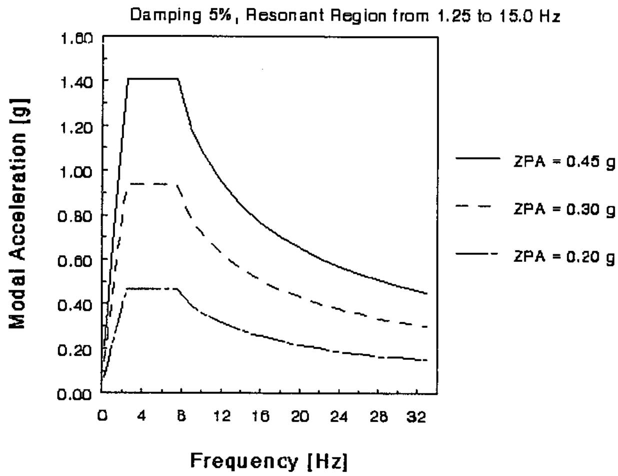

Fig. 2 Pipe Group F, ZPA = 0.30 g

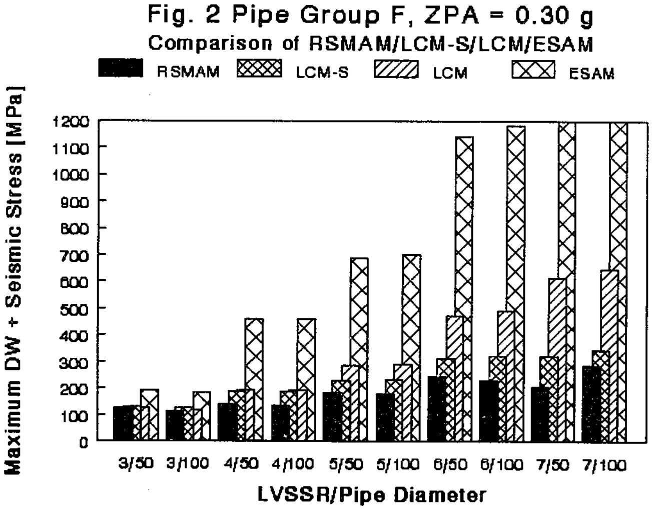

Table 1 Recommended LVSSRs for Pipe Segments A-H, Diameter (D) from 25 to 50 mm, Schedule 40 or 80, Material SA 106 Grade B (ASME BPVC) or Similar, Socket Welding Connections and Fittings, Primary Stress Indice B_2 = 1.5, Class 2 and 3, Service Level D, Pipe Location up to 12 m Above Grade

ZPGA/ZPA (floor)	0.30 g / 0.45 g			0.20 g / 0.30 g			0.10 g / 0.15 g		
Governing Criteria[1]	(a)	(b)	(c)	(a)	(b)	(c)	(a)	(b)	(c)
B	4	5	7	4-5[3]	6	7	5-6[3]	7	7
C	4	5-6[3]	7	5	6-7[3]	7	6-7[3]	7	7
D	4	5-6[3]	7	5	6-7[3]	7	6	7	7
E	4	5-6[3]	7	5	6-7[3]	7	6-7[3]	7	7
F	3-4[3]	4-5[3]	$\underline{5}$[7]	4	5	6	5	6	7
G	3	4	5	3-4[3]	4-5[3]	5-6[3]	4-5[3]	5-6[3]	7
H	3-4[3]	5	6	4	5-6[3]	7	5-6[3]	7	7

Table 2 Recommended LVSSRs for Pipe Segments A-H, Diameter (D) from 50 to 100 mm, Schedule 40 or 80, Material SA 106 Grade B (ASME BPVC) or Similar, Butt Welding Connections and Fittings, Primary Stress Indice B_2 = from 1.53 to 2.82, Class 2 and 3, Service Level D, Pipe Location up to 12 m Above Grade

ZPGA/ZPA (floor)	0.30 g / 0.45 g			0.20 g / 0.30 g			0.10 g / 0.15 g		
Governing Criteria[1]	(a)	(b)	(c)	(a)	(b)	(c)	(a)	(b)	(c)
A1, A2[5]	4	5	6	4-5[3]	6	7	6	7	7
B R≥4xD[4]	4	5-6[3]	7	5	6	7	6	7	7
1.5xD≤R≤4xD	$\underline{4}$[7]	$\underline{4}$[7]	$\underline{4}$[7]	5	6	7	6	7	7
C R≥4xD	5	6	7	5-6[3]	7	7	7	7	7
1.5xD≤R≤4xD	5	6	7	5-6[3]	7	7	7	7	7
D[6]	4-5[3]	$\underline{6}$[7]	$\underline{6}$[7]	5-6[3]	7	7	7	7	7
E R≥4xD	4-5[3]	6	7	5	7	7	7	7	7
1.5xD≤R≤4xD	4-5[3]	$\underline{5}$[7]	$\underline{5}$[7]	5	7	7	7	7	7
F R≥4xD	3-4[3]	5	$\underline{5}$[7]	4	5	6	5	6-7[3]	7
1.5xD≤R≤4xD	$\underline{3}$[7]	$\underline{3}$[7]	$\underline{3}$[7]	$\underline{4}$[7]	$\underline{4}$[7]	$\underline{4}$[7]	5	6-7[3]	7
G R≥4xD	3	4	4-5[3]	4	4-5[3]	5-6[3]	5	6	7
1.5xD≤R≤4xD	3	4	4-5[3]	4	4-5[3]	5-6[3]	5	6	7
H R≥4xD	4	5	6	5	6	7	6	7	7
1.5xD≤R≤4xD	$\underline{3}$[7]	$\underline{3}$[7]	$\underline{3}$[7]	5	6	6	6	7	7

Notes: (1) Governing criteria :

(a) $\sigma_{max,DW+seismic} \leq S_{adm}$ and $u_{max,hor} \leq 250$ mm (b) $\sigma_{max,DW+seismic} \leq S_{adm}$ and $u_{max,hor} \leq 500$mm (c) $\sigma_{max,DW+seismic} \leq S_{adm}$ and $u_{max,hor} \leq 750$ mm,

($S_{adm} = 3.0xS_h$ but not greater than $2.0xS_y$, where S_h and S_y are the basic material allowable stress and the material yield stress respectively, strongly according to the current ASME BPVC, Section III, Class 2 and 3, Service Level D, while $u_{max,hor}$ is the maximum horizontal pipe displacement, the limit values of 250, 500, and 750 mm are taken from experience).

(2) Support reaction should be evaluated using formulas (3) to (6).

(3) Higher values shown could be used when the pipe segment is suspended by ductile pendulum type hangers.

(4) R = bend radius of elbows, primary stress indice B_2 = 1.53 and 2.82 for R = 4xD and 1.5xD respectively.

(5) Only straight pipe elements.

(6) Primary stress indices for butt welding tees (diameter up to 100 mm) B_2 = 2.16 and B_2 = 1.73 for the tee run and branch respectively.

(7) The underlined number means that in this case the stress criterion is governing rather than horizontal displacements.

(8) LVSSR = Lateral to Vertical Support Span Ratio, the DW span = 2.13, 3.05, 3.66, amd 4.27 m for D = 25, 50, 75,and 100 mm, where D = the nominal pipe diameter (Table NF-3611-1, ASME BPVC, Section III).