# SEISMIC DESIGN OF SMALL DIAMETER PIPE AND TUBING FOR NUCLEAR POWER PLANTS

by

J. D. Stevenson[I]

## SYNOPSIS

This paper presents a simplified seismic design method for small diameter piping systems where complete or rigorous dynamic analysis is not feasible. This procedure utilizes a coefficient to be applied to the peak of the applicable single degree of freedom floor or ground response spectrum in order to determine seismic design loads. The procedure has been correlated with dynamic multidegree of freedom modal analysis results from a number of actual nuclear plant systems. Seismic loads determined by this procedure are quite conservative in the mean when compared with complete dynamic analysis.

## INTRODUCTION

Seismic design of building structures has been a standard requirement in earthquake prone regions since the early 1920's. In general, this design has been carried out using static methods of analysis as expressed by national building codes[(1)]. During the last 10 to 15 years for major structures where potential replacement costs or consequences of failure have warranted, more rigorous analyses have been performed. In such cases, seismic response spectra coupled with dynamic multidegree of freedom modal analysis have been used.

Within the past 5 to 10 years the response spectra-modal dynamic analysis methods have been extended to design of safety related fluid and electrical systems associated with nuclear power plants.

At the present time the dynamic analysis of the major piping systems which circulate nuclear reactor coolant fluid and provide steam to drive the generator turbines has become quite routine. There are, however, still many tens of thousands of feet of conduits consisting of smaller diameter piping, tubing, electrical conduit raceways and ductwork which serve a safety function and therefore require a determination of seismic design adequacy. The cost of analyzing fluid and electrical distribution system regardless of size using rigorous dynamic analysis methods is typically in excess of $10 per foot. Clearly such methods of analysis are not feasible for the vast majority of systems. This paper is an attempt to develop simplified methods of analysis which can be used on smaller piping, tubing, raceways, etc., but which still can be shown to provide conservative seismic designs.

[I]Consulting Engineer, Westinghouse Nuclear Energy Systems, Pittsburgh, Pennsylvania.

## SEISMIC DESIGN COEFFICIENTS

Probably the simplest approach is to make all systems relatively rigid (i.e., fundamental frequencies typically above 33 Hz when using the Newmark response spectra for 2.0 percent damping[2]). If this were done, building or supporting structures and therefore the systems could be analyzed using the same seismic motions as the supporting structure. This motion would be known from the building or support structure seismic analysis. Unfortunately, the development of such high frequency response would typically require approximately a doubling of the number supports normally required. As an example, the dead weight hanger spacing as recommended by the ANSI B31.1 code[3] would result in fundamental frequencies as shown in Table 1 for standard weight pipe. An indication of the effect of span length on frequency is shown in Table 2[4]. In addition, particularly in high temperature fluid systems the required closeness of supports would normally lead to higher thermal stresses thereby reducing the overall reliability of the system. This approach except in specific instances is not feasible from either a cost or an improved reliability standpoint.

It has long been recognized that approximate seismic analyses could be performed as a function of the peak of the applicable floor response spectrum. The value thus determined, usually in the form of an acceleration level coefficient, $k_s$, is applied to the mass distribution of the system to develop a static force on the systems so that seismic stresses may be determined. The controversy usually has been raised concerning what is a conservative coefficient to use. Regulatory authorities have usually argued that since the floor response spectra is for a single degree of freedom system, multidegree of freedom response of the system being considered could result in a response in excess of that determined for a single degree of freedom system. The value of 1.3 has been applied in the U. S.[5] as a multiplier to be applied to the peak of the single degree of freedom floor response spectrum to account for this effect. Designers, on the other hand, argue that the probability of any particular system being exactly at the resonant frequency or peak of the floor response spectrum and remaining at that frequency during a significant buildup of inertia load response is extremely remote for the relatively low damped systems being considered. In addition, typical nonlinearities such as joint slippage, normal cracking of concrete supports, closing of gaps or changes in support configuration all tend to detune the system and lessen amplified response to seismic loads in resonance regions. The seismic support design of several piping systems which were based on the peak of the floor response spectra applied as a static g load has been compared with the results of dynamic analysis of the same lines as shown in Table 3. In all cases evaluated, the percent critical damping was 0.5 percent and the total allowable stress in the pipe including dead and pressure as well as seismic load effects was taken as 1.2S where S was defined as the allowable stress in the pipe due to pressure acting alone. A statistical evaluation of the results of the dynamic analyses was performed assuming maximum seismic stress allowable, $S_s$ equal to 0.6S which results from a maximum 1.2S allowable minus an allowance of 0.1S for dead load and 0.5S for pressure. The average value of the peak seismic stress determined in each line as a function of the maximum allowable seismic stress was $0.340S_s$ with a standard deviation equal to $0.292S_s$. Assuming a normal distribution, this results in a probability of exceeding the seismic limit of 0.6S is 0.012 and the total stress limit of 1.2S is 0.004. Actually, the distribution of probabilities is somewhat skew positive more characteristic of a log normal distribution so the probabilities indicated are only approximate.

## SUGGESTED DESIGN PROCEDURES

All conduit systems regardless of whether they are analyzed statically or dynamically must be laid out to include support locations so that they can be evaluated for all load conditions. Preferably, this is done following simple design rules which result in an adequate but not overly conservative design. The procedure suggested in this paper was developed specifically for piping systems. However, it can be applied to raceways and ductwork by defining applicable stress limits for these conduits.

Piping which is typically continuous over several intermediate supports has resultant bending moments as follows:

$$M = 0.1Wl^2 \qquad (1)$$

where:

M = maximum bending moment in pipe (lbs/in)

W = effective load on the pipe (lbs/in)

l = span length between supports (in)

This moment of course can approach that of a simply supported beam or $0.125Wl^2$ at the center of continuous span if the mode of the continuous span is excited so that inertia loads in alternate spans have opposite sign. However, the probability of this occurring is considered small enough to permit the use of equation 1 for design purposes. The maximum resultant stress in the pipe is determined

$$S_h = \frac{M}{Z} \qquad (2)$$

where:

$S_h$ = maximum bending stress in pipe at temperature (psi)

Z = elastic section modulus of pipe ($in^3$)

The current stress limit for the American Society of Mechanical Engineers (Winter, 1973 Addendum) - ASME Section III-NC class 2 piping considering dead and seismic loads is expressed

$$\frac{P\ max\ Do}{4t_n} + .75i\ \left(\frac{M_A + M_B}{Z}\right) \leq 1.2S_h \qquad (3)$$

for primary loads and

$$\frac{PDo}{4t_n} + .75i\ (M_A/Z) + i\ (M_C/Z) \leq (S_h + S_A) \qquad (4)$$

for primary plus secondary stress

where:

- $P$ = internal design pressure, psig
- $Do$ = outside diameter of pipe, in.
- $t_n$ = nominal walls thickness of component, in.
- $M_A$ = resultant moment loading on cross-section due to weight and other sustained loads, lb/in.
- $Z$ = elastic section modulus of pipe, $in^3$.
- Pmax = peak pressure, psig resulting from pressure transient except it can be considered equal to P unless the pressure transient is considered concurrently with earthquake.
- $i$ = stress intensification factor developed at points of discontinuity or bends.
- $M_B$ = resultant moment loading on cross-section due to occasional loads such as thrusts from relief and safety valves; loads from pressure and flow transients; and earthquake.
- $M_C$ = range of resultant moments due to thermal expansion. Also includes moment effects of anchor displacements due to earthquake.
- $S_a$ = the allowable stress range for expansion stresses as defined by code.
- $S_h$ = basic material allowable stress at maximum heat temperature. as defined by code.

Assuming in the limit that $0.5S_h$ is reserved for pressure stress and $0.1S_h$ is reserved for dead weight stress, a resultant $0.6S_h$ is available to carry seismic load. Substituting $0.6S_h$ for the allowable stress in Equations (1) and (2), it is possible to solve for the maximum span between supports not to exceed that stress

$$1 = 2.45\ (S_h Z/k_s W)^{1/2} \qquad (5)$$

where:

$k_s$ = the effective seismic coefficient expressed in gravities

W = weight distribution of the pipe (lbs/in)

1 = span length between seismic supports (in)

Of course, the routing of pipe is seldom on a continuous straight line basis so that design groups have developed design aids for use by their support layout designers which consider in graphic form a variety of typical bend configurations and spans between supports in terms of the span length developed in Equation (5) which assure the seismic stress limits are not exceeded. Concentrated loads such as valves in the piping system are represented as equivalent distributed mass. It remains only to define a value for the seismic coefficient $k_s$ in Equation (5) which assures an adequate design.

## CONCLUSIONS AND RECOMMENDATIONS

Statistical evaluation of the comparison of dynamic verification of static analysis for cases given in Table 3 normalized to the current ASME Class 2 piping criteria would indicate a probability of exceeding seismic and total stress limits for a range of assumed $k_s$ values taken as a coefficient times the peak of the floor response spectra as shown in Table 4.

It is recommended that a value of $k_s$ equal to 0.85 times the peak of the applicable floor response spectra be used with the design procedures outlined herein. It should be noted that the percent critical damping considered in this study was relatively low being approximately 0.5 percent. There is currently a trend to increase the damping assumed in the design of conduit systems as the result of correlation with recent test results.(6) Since broader response bands can be expected with the use of higher damping values, seismic coefficients for $k_s$ should be increased as a function of higher damping values. Lacking any definitive results, it is suggested a value of 1.0 times the peak be used for 2.0 percent and above damping. It should be understood that the conclusions reached herein are based on a somewhat limited correlation with existing data. It is hoped as more design data becomes available, the recommendation made herein will be tested against this additional information.

## REFERENCES

(1) International Conference of Building Officials, Uniform Building Code, 6th Edition, 1970.

(2) Newmark, N. M., "Earthquake Response of Reactor Structures", presented at the 1st International Conference on Structural Mechanics in Reactor Technology, Berlin, W. Germany, September 20-24, 1971.

(3) ANSI B31.1.0-1967, "Power Piping", American National Standards Institute, New York.

(4) E. C. Rodabaugh and A. G. Pickett, "Survey Report on Structural Design of Piping Systems and Components", TID-25553, December 1970.

(5) USAEC Docket 50-261-35, "H. B. Robinson Unit No. 2. Additional Information Concerning Seismic Analysis of Class 1 Piping and Equipment", June 1970.

(6) A. Morrone, "Damping Values of Nuclear Power Plant Components", WCAP-7921, November 1972.

(7) R. C. King, "Piping Handbook", 5th Ed., McGraw-Hill, New York, 1967.

(8) R. J. Roark, "Formulas for Stress and Strain", 4th Ed., McGraw-Hill, New York, 1965.

TABLE 1

PIPING FUNDAMENTAL FREQUENCIES AS A FUNCTION OF ANSI B 31.1 SUGGESTED DEAD WEIGHT SUPPORT SPACING

| Pipe Size (Std) | Weight-lbs. Water/ ft | Steam/ ft | $L_w$ ft | $L_s$ ft | $L_w^3$ x$10^6$ in.$^3$ | $L_s^3$ x$10^6$ in.$^3$ | I in$^4$ | $W_w$ lbs | $W_s$ lbs | $f_w$ $H_z$ | $f_s$ $H_z$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1" | 2.053 | 1.68 | 7 | 9 | .593 | 1.26 | .0874 | 15.10 | 14.05 | 16.70 | 11.85 |
| 2" | 5.108 | 3.66 | 10 | 13 | 1.732 | 3.80 | .666 | 51.08 | 47.60 | 14.85 | 10.25 |
| 3" | 10.78 | 7.59 | 12 | 15 | 2.98 | 5.83 | 3.02 | 129.0 | 114.0 | 16.23 | 11.40 |
| 4" | 16.30 | 10.8 | 14 | 17 | 4.74 | 8.49 | 7.23 | 228.0 | 183.7 | 13.80 | 11.56 |
| 6" | 31.48 | 19.0 | 17 | 21 | 8.52 | 16.00 | 28.14 | 535.0 | 399.0 | 13.30 | 11.20 |
| 8" | 50.24 | 28.6 | 19 | 24 | 11.84 | 23.89 | 72.5 | 955.0 | 686.0 | 13.50 | 11.20 |
| 12" | 98.60 | 49.6 | 23 | 30 | 21.00 | 46.66 | 279.3 | 2270 | 1490 | 12.95 | 10.70 |
| 16" | 141.68 | 62.6 | 27 | 35 | 34.05 | 74.09 | 562 | 3820 | 2195 | 11.13 | 9.95 |
| 20" | 204.60 | 78.7 | 30 | 39 | 46.60 | 102.50 | 1114 | 6140 | 3070 | 10.70 | 10.15 |
| 24" | 278.48 | 94.62 | 32 | 42 | 56.70 | 128.02 | 1943 | 8930 | 3980 | 10.40 | 10.40 |

NOTES:

1. Fundamental Pipe Properties from King(7)
2. Frequencies Determined = $3.55\ (5Wl^3/384\ EI)^{1/2}$ from Roark(8)
3. $E = 29 \times 10^6$ psi

TABLE 2

FREQUENCY AND LENGTH RELATIONSHIPS FOR PIPE SPANS

| Pipe | | L, Ft. (1) | $f_n$ (4) | | $f_n$ = 35 cps (5) |
| --- | --- | --- | --- | --- | --- |
| Size | Sch. | | Empty (2) | Full (3) | |
| 1 | 80 | 7 | 12.8 | 12.3 | 4.1 |
| | 160 | 7 | 12.9 | 12.7 | 4.2 |
| 2 | 80 | 10 | 13.4 | 12.4 | 5.9 |
| | 160 | 10 | 13.5 | 12.9 | 6.0 |
| 4 | 80 | 14 | 14.0 | 12.6 | 8.4 |
| | 160 | 14 | 14.2 | 13.3 | 8.6 |
| 8 | 80 | 19 | 15.9 | 13.6 | 11.8 |
| | 160 | 19 | 15.8 | 14.5 | 12.2 |
| 12 | 80 | 23 | 16.6 | 13.9 | 14.5 |
| | 160 | 23 | 16.3 | 14.9 | 15.0 |
| 16 | 80 | 27 | 15.2 | 12.7 | 16.3 |
| | 160 | 27 | 14.9 | 13.6 | 16.8 |
| 24 | 80 | 32 | 16.6 | 13.6 | 20.0 |
| | 160 | 32 | 16.2 | 14.6 | 20.7 |

NOTES:

(1) L is support spacing taken from the Piping Handbook, Reference 7, p. 5-4. This value of L is based on 1500 psi stress or 1/10" deflection, water-filled pipe.

(2) Empty includes weight of pipe plus weight of insulation. Insulation assumed to weigh 16 lb/cu-ft., 2" thick for 1" and 2"; 2.5" thick for 4", 8", and 12" and 3" thick for 16" and 24" pipe.

(3) Full includes weight of pipe, insulation and water.

(4) $f_n$ = first mode frequency in cycles per second for span with simply supported ends.

TABLE 3

DYNAMIC ANALYSIS STRESS DATA

| LINE NO. | LINE SIZE | MAX.SEISMIC CAL. STRESS $S_s$ | ALL.SEISMIC STRESS (0.6S) | RATIO ($S_s$/0.6S) | MAX.TOTAL CAL.STRESS ($S_t$) | ALL.TOTAL STRESS (1.2S) | RATIO $S_t$/1.2S | REMARKS $(\bar{X}_s-X_s)$ | $(\bar{X}_s-X_s)^2$ | $(\bar{X}_t-X_t)$ | $(\bar{X}_t-X_t)^2$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 12" | 6,887 | 7,350 | .937 | 13,306 | 14,700 | .905 | .597 | .356 | .550 | .302 |
| 2 | 18" | 7,313 | 9,000 | .813 | 9,319 | 18,000 | .518 | .473 | .224 | .163 | .027 |
| 3 | 18" | 9,490 | 9,000 | 1.054 | 14,307 | 18,000 | .795 | .714 | .510 | .440 | .194 |
| 4 | 8" | 5,550 | 11,250 | .493 | 7,993 | 22,500 | .355 | .153 | .023 | 0 | 0 |
| 5 | 4" | 2,782 | 8,760 | .261 | 9,922 | 17,520 | .567 | .079 | .006 | .212 | .045 |
| 6 | 4" | 1,306 | 8,250 | .159 | 2,806 | 16,500 | .170 | .181 | .032 | .185 | .034 |
| 7 | 12" | 5,439 | 7,200 | .755 | 7,992 | 14,400 | .555 | .415 | .172 | .200 | .040 |
| 8 | 12" | 5,805 | 7,200 | .806 | 9,353 | 14,400 | .650 | .566 | .320 | .295 | .087 |
| 9 | 16" | 1,969 | 9,000 | .219 | 5,211 | 18,000 | .290 | .121 | .015 | .065 | .004 |
| 10 | 6" | 1,717 | 7,200 | .238 | 3,444 | 14,400 | .239 | .102 | .010 | .116 | .014 |
| 11 | 6" | 6,157 | 7,350 | .838 | 11,200 | 14,700 | .762 | .489 | .249 | .407 | .166 |
| 12 | 4" | 1,495 | 7,140 | .210 | 8,208 | 14,280 | .576 | .130 | .017 | .221 | .049 |
| 13 | 3" | 1,740 | 7,140 | .244 | 6,252 | 14,280 | .438 | .096 | .009 | .083 | .007 |
| 14 | 14" | 2,916 | 6,930 | .421 | 10,458 | 13,860 | .755 | .081 | .007 | .400 | .160 |
| 15 | 3" | 2,833 | 7,140 | .397 | 8,135 | 14,280 | .570 | .057 | .003 | .215 | .048 |
| 16 | 1" | 2,382 | 7,140 | .334 | 7,466 | 14,280 | .523 | .006 | .000 | .168 | .028 |
| 17 | 10" | 2,615 | 7,200 | .363 | 4,285 | 14,400 | .298 | .023 | .000 | .057 | .003 |
| 18 | 6" | 1,838 | 7,200 | .255 | 2,919 | 14,400 | .203 | .085 | .007 | .152 | .023 |
| 19 | 3" | 263 | 7,200 | .036 | 1,330 | 14,400 | .092 | .304 | .093 | .263 | .069 |
| 20 | 8" | 3,872 | 7,200 | .538 | 5,171 | 14,400 | .359 | .198 | .040 | .004 | — |
| 21 | 10" | 1,595 | 9,000 | .177 | 4,652 | 18,000 | .258 | .163 | .026 | .097 | .009 |
| 22 | 14" | 2,379 | 9,000 | .264 | 4,625 | 18,000 | .257 | .076 | .006 | .098 | .010 |
| 23 | 8" | 493 | 7,200 | .068 | 2,379 | 14,400 | .165 | .272 | .074 | .185 | .034 |
| 24 | 10" | 7,876 | 9,600 | .820 | 12,865 | 19,200 | .670 | .480 | .230 | .315 | .099 |
| 25 | 6" | 311 | 9,000 | .035 | 1,022 | 18,000 | .057 | .305 | .093 | .298 | .089 |
| 26 | 24" | 8,910 | 9,000 | .990 | 13,739 | 18,000 | .763 | .650 | .423 | .408 | .167 |
| 27 | 20" | 2,682 | 9,000 | .298 | 6,459 | 18,000 | .359 | .042 | .002 | .004 | — |
| 28 | 24" | 4,316 | 9,000 | .480 | 8,070 | 18,000 | .448 | .140 | .020 | .093 | .009 |
| 29 | 24" | 3,333 | 9,000 | .370 | 7,075 | 18,000 | .393 | .030 | .001 | .038 | .002 |
| 30 | 20" | 2,682 | 9,000 | .298 | 6,588 | 18,000 | .366 | .042 | .002 | .011 | — |
| 31 | 20" | 3,778 | 9,000 | .420 | 7,429 | 18,000 | .413 | .080 | .006 | .058 | .003 |
| 32 | 6" | 1,878 | 9,000 | .209 | 2,578 | 18,000 | .143 | .131 | .017 | .212 | .047 |
| 33 | 18" | 6,983 | 10,500 | .665 | 13,887 | 21,000 | .661 | .325 | .106 | .306 | .093 |
| 34 | 18" | 7,897 | 10,500 | .752 | 15,286 | 21,000 | .728 | .412 | .170 | .373 | .139 |
| 35 | 18" | 4,600 | 10,500 | .438 | 11,814 | 21,000 | .563 | .098 | .010 | .208 | .043 |
| 36 | 18" | 5,800 | 10,500 | .552 | 12,698 | 21,000 | .605 | .212 | .045 | .250 | .063 |
| 37 | 10" | 726 | 9,000 | .081 | 1,601 | 18,000 | .089 | .259 | .067 | .266 | .071 |
| 38 | 12" | 1,253 | 9,000 | .139 | 2,218 | 18,000 | .123 | .201 | .040 | .232 | .054 |
| 39 | 8" | 2,336 | 11,216 | .208 | 4,317 | 22,433 | .192 | .132 | .017 | .163 | .027 |
| 40 | 12" | 2,747 | 11,216 | .245 | 2,747 | 22,433 | .122 | .095 | .009 | .233 | .054 |
| 41 | 8" | 2,180 | 11,216 | .194 | 4,321 | 22,433 | .192 | .146 | .021 | .163 | .027 |
| 42 | 8" | 814 | 11,036 | .074 | 2,367 | 22,433 | .105 | .266 | .071 | .250 | .063 |
| 43 | 6" | 536 | 11,146 | .048 | 1,792 | 22,073 | .081 | .292 | .085 | .274 | .075 |
| 44 | 6" | 647 | 11,146 | .058 | 2,184 | 22,293 | .098 | .282 | .080 | .257 | .066 |
| 45 | 8" | 499 | 11,141 | .045 | 2,171 | 22,293 | .098 | .295 | .085 | .257 | .066 |
| 46 | 6" | 1,031 | 11,141 | .093 | 2,898 | 22,283 | .130 | .247 | .061 | .225 | .051 |
| 47 | 8" | 602 | 11,141 | .054 | 2,764 | 22,283 | .121 | .286 | .082 | .234 | .055 |
| 48 | 8" | 431 | 11,231 | .038 | 1,931 | 22,283 | .087 | .302 | .091 | .268 | .072 |
| 49 | 8" | 834 | 11,231 | .074 | 2,334 | 22,463 | .104 | .266 | .071 | .251 | .063 |
| 50 | 18" | 708 | 11,231 | .063 | 2,208 | 22,463 | .098 | .277 | .077 | .257 | .066 |
| 51 | 14" | 507 | 11,231 | .045 | 4,055 | 22,463 | .181 | .295 | .085 | .174 | .030 |
| 52 | 14" | 340 | 11,231 | .030 | 3,888 | 22,463 | .173 | .310 | .096 | .182 | .033 |

$$\bar{X}_s = \frac{X_s}{n} = 17.696/52 = 0.340$$

$$\bar{X}_t = \frac{X_t}{n} = 18.463/52 = 0.355$$

$$\sigma_s^2 = \frac{(\bar{X}_s - X_s)^2}{n-1} = 4.362/51 = .085 \qquad \sigma_s = 0.292$$

$$\sigma_t^2 = \frac{(\bar{X}_t - X_t)^2}{n-1} = 2.980/51 = .058 \qquad \sigma_t = 0.241$$

TABLE 4

PROBABILITY OF EXCEEDING SEISMIC STRESS ALLOWABLE AS A FUNCTION OF SEISMIC LOAD COEFFICIENT $K_s$

| $K_s$ | $\overline{X}_s$ | S.D. | $f_s$ |
|---|---|---|---|
| 0.50 | .680 | 1.10 | 0.14 |
| 0.67 | .510 | 1.68 | 0.05 |
| 0.75 | .453 | 1.88 | 0.03 |
| 0.875 | .389 | 2.08 | 0.02 |
| 1.000 | .340 | 2.26 | 0.012 |
| 1.30 | .261 | 2.53 | 0.006 |
| 1.50 | .227 | 2.65 | 0.004 |
| 1.75 | .194 | 2.76 | 0.0029 |
| 2.00 | .170 | 2.84 | 0.0023 |

WHERE:

$\overline{X}_s$ = Mean Seismic Stress as a Function of the Maximum Allowable Seismic Stress $S_s$.

S.D. = Number of Standard Deviation between Mean and Limiting Value.

$f_s$ = Probability of Exceeding Allowable Seismic Stress Based on Normal Distribution.