SEISMIC ISOLATION OF BRIDGES
(Unpublished Paper)

Analysis of Various Isolation Systems for a Multi-Girder Highway Bridge

by

M.C. Constantinou
Department of Civil Engineering
State University of New York
Buffalo, NY 14260

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SEISMIC ISOLATION OF BRIDGES

1. INTRODUCTION

Designs of seismic isolation systems for a steel multi-girder highway bridge are presented. The gravity loads on the bearings of this bridge are low, and this complicates the design of the isolation system. The selection of this bridge has been deliberate in order to demonstrate, and to a certain extent overstate, the problems with some isolation systems in bridge applications.

The design and analysis processes are kept simple enough so that we understand what we are doing.

2. HIGHWAY BRIDGE

Figure 1 shows a single-span highway bridge. It consists of five girders and it will be supported by ten bearings.

We consider that the 1991, 1992 AASHTO specs. apply. The bridge is located on soil profile type II in an area with $A = 0.6$.

The isolation performance criteria call for a design with minimum displacement in the superstructure provided that the force in the substructure does not exceed 30% of the supported weight.

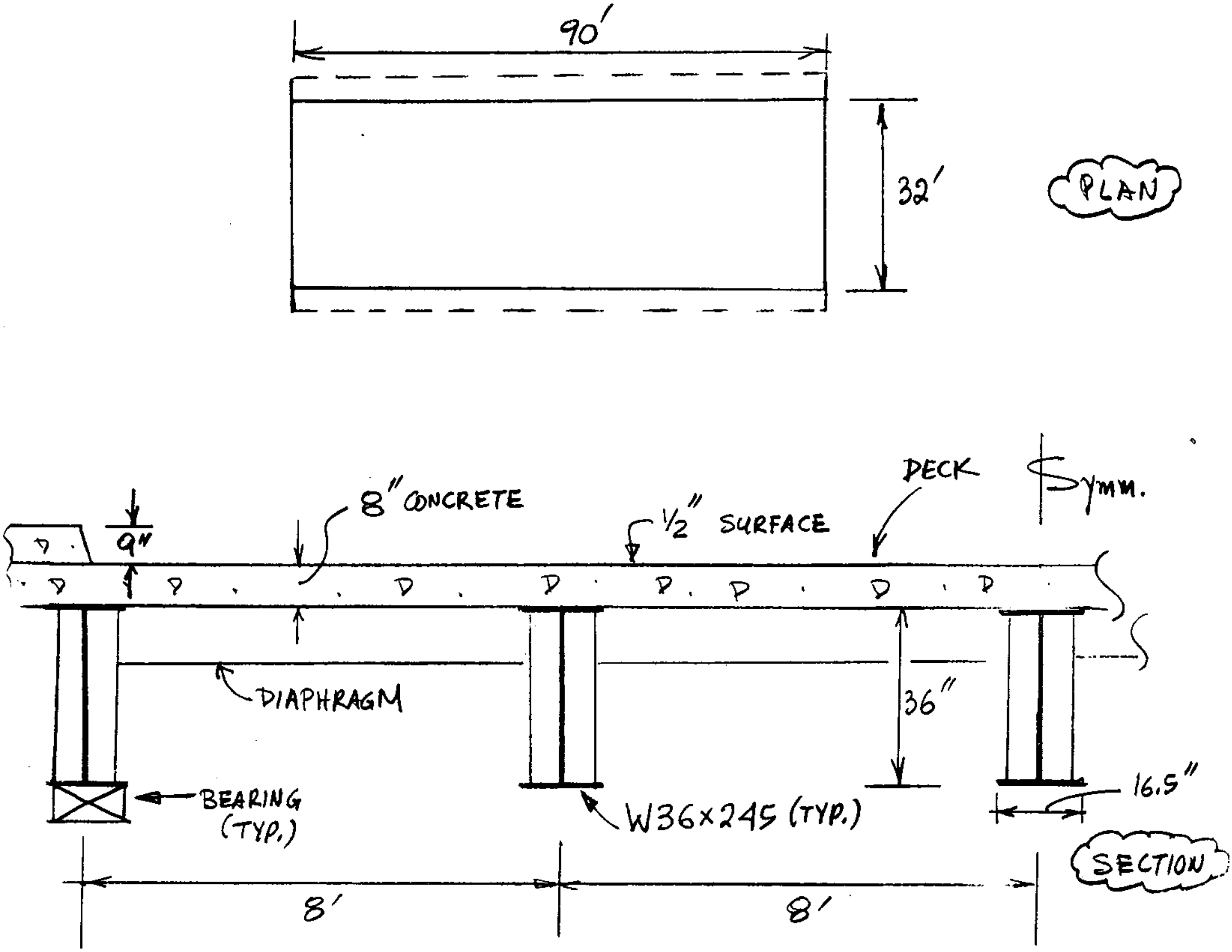


FIGURE 1 Highway Bridge

3. LOADING CALCULATIONS

WEIGHT : CONCRETE $\frac{8}{12} \times 150 = 100\ psf$

$\frac{1}{2}''$ SURFACE $25\ psf$

$\left.\begin{array}{l} 100\ psf \\ 25\ psf \end{array}\right\} 125\ psf$

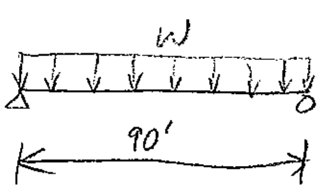
WEIGHT PER GIRDER : $125\ psf \times 8' = 1\ K/ft + \underbrace{0.245\ K/ft}_{\text{GIRDER WEIGHT}} \approx 1.25\ K/ft$

TOTAL BRIDGE WEIGHT : $5 \times 1.25 \times 90 = 562.5$ Kips

LOAD PER BEARING : $P = \frac{562.5}{10} = \underline{\underline{56.25\ Kips}}$

ROTATION (SIMPLY SUPPORTED 90' GIRDER UNDER 1.25 K/ft LOAD, $I = 16100\ in^4$, $E = 29000$ ksi)

$$\Theta = \frac{WL^3}{24EI} = \frac{1.25/12 \times (90 \times 12)^3}{24 \times 29000 \times 16100} = \underline{\underline{0.01171\ rad.}}$$



4. DESIGN OF HIGH DAMPING RUBBER BEARING ISOLATION SYSTEM

Properties of high damping rubber bearings produced in the U.S. and Italy (type used in Foothill's Building in CA) are shown in Figure 2. The figure presents values of the secant (effective) shear modulus and damping ratio β under scragged conditions. The presented properties are valid for frequencies in the range 0.3 to 0.7Hz, shape factor $S \geq 10$ and temperature of about 70°F (20°C). Under fresh conditions, the rubber has an elongation at break (ε_u or EB) equal to 5.5.

It should be noted that under unscragged conditions, this high damping rubber exhibits much higher stiffness (approximately 50% more) and about the same damping ratio as under scragged conditions. Unscragged conditions have been typically disregarded in

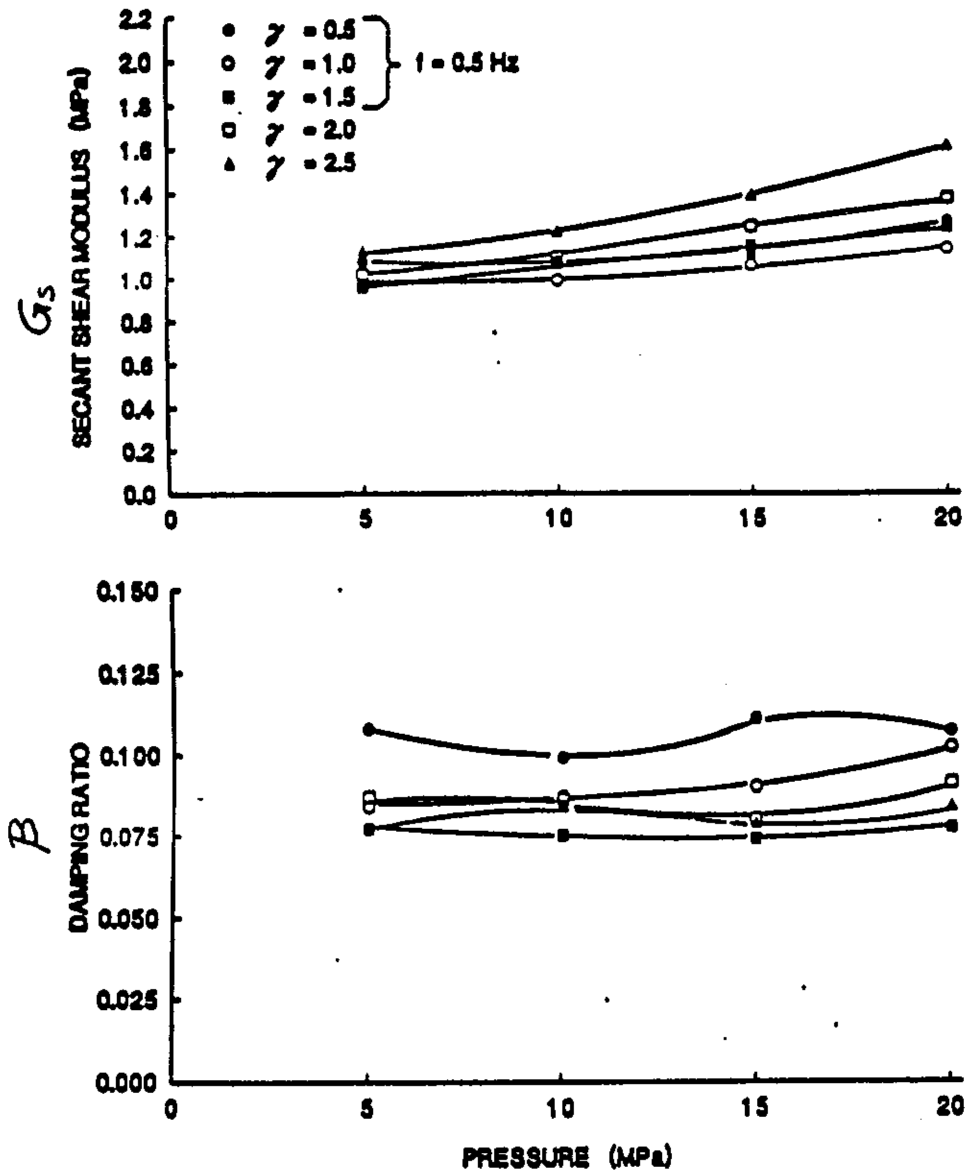


FIGURE 2 Properties of High Damping Rubber for Scragged Conditions (1MPa = 145 psi)

design in the past. However, recent evidence on the possible recovery to the unscragged conditions in short time have led to their consideration in a number of projects (see ATC-17-1 Seminar on Seismic Isolation). Herein, we consider only the scragged properties of rubber. We furthermore neglect the effects of aging, low temperature and variation in properties for the design. Consideration of these effects will inevitably alter the design. Since consideration of these effects results in increases of the effective stiffness of bearings, the design may be entirely dominated by these conditions to the point that high damping rubber bearings may be unsuitable for light load applications.

The 1991 AASHTO Guide Specs for Seismic Isolation specify:

Design Displacement
$$d_i = \frac{10 A S_i T_e}{B} \tag{1}$$

Elastic Seismic Response Coefficient
$$C_s = \frac{\sum K_{eff}}{W} d_i \tag{2}$$

Effective Period
$$T_e = 2\pi \sqrt{\frac{W}{g \sum K_{eff}}} \tag{3}$$

Combination of Eqs. (1) to (3) gives

$$C_s = \frac{40\pi^2 A S_i}{g T_e B} \tag{4}$$

Based on the properties of Figure 2 and for pressure below 5 MPa (= 725 psi), $G_s \approx 1$ MPa = 145 psi and $\beta = 0.08 - 0.10$. Assume $\beta = 0.10$. Based on BE 1/76, a value of $G = 1$ MPa = 145 psi corresponds to $E = 4G$ and $\kappa = 0.57$.

Requiring $C_s = 0.3$ with $A = 0.6$, $S_i = 1.5$, $B = 1.2$ ($\beta = 0.10$),

Eqn. (4) gives

$$C_s = \frac{0.766}{T_e} = 0.3 \rightarrow \underline{T_e = 2.55 \text{ secs}}$$

NOTE THAT DAMPING FORCE WAS NOT INCLUDED IN CALCULATION OF C_s

Eqn. (1) gives $\underline{d_i = 19.13 \text{ in.}}$

Eqn. (3) gives for $W = 562.5$ Kips, $\Sigma K_{eff} = \underset{\text{BEARINGS}}{10} \left(\frac{G_s A}{T}\right)$

$$\frac{G_s A}{T} = \frac{4\pi^2 W}{10 g T_e^2} = 0.884 \text{ K/in}$$

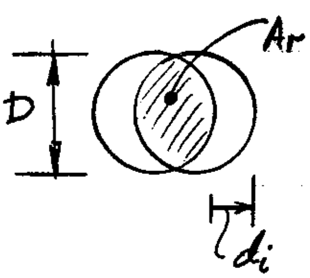
where

A = bonded rubber area, T = total rubber thickness and $G_s = 145$ psi.

⊛ say $T = 15$ in. $\rightarrow A = 91.45 \text{ in}^2 \Rightarrow$ DIA. $\underline{D = 10.8 \text{ in.}}$

REDUCED AREA: $A_r = (\alpha - \sin\alpha)\frac{D^2}{4}$

$\alpha = 2\cos^{-1}\left(\frac{d_i}{D}\right)$



A_r is negative, strains are unacceptably large. (5)
Furthermore, bearing is unstable. (6)

One may go through an endless cycle of trials to confirm that the design of a high damping ($\beta = 0.10$) rubber system for this bridge is not possible for the condition $C_s \le 0.3$.

The situation is somehow improved by modifying the bridge design to accept four rather than ten bearings. This requires the use of a deep cross-girder as shown in Figure 3.

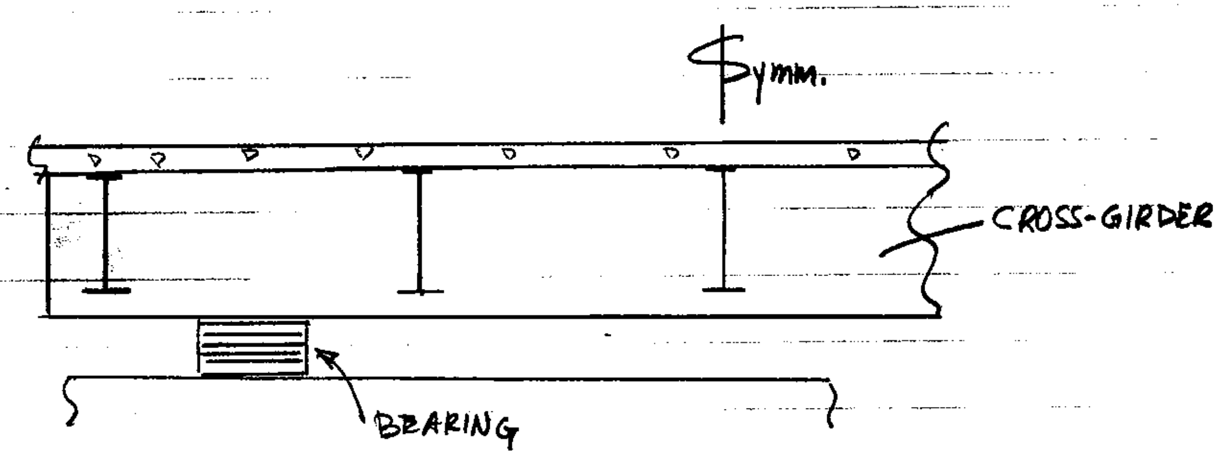


FIGURE 3 Modified Bridge with Four Bearings

In the modified design $T_e = 2.55$ secs and $d_i = 19.13$ in.

However, $\Sigma K_{eff} = 4\left(\frac{G_s A}{T}\right)$, so that Eqn. (3) gives

$$\frac{G_s A}{T} = \frac{\pi^2 W}{g T_e^2} = 2.21 \text{ K/in}\Big|_{\text{EACH BEARING}}$$

A design with $T = 29.625$ in. (!) and DIA. $D = 24$ in.

gives $\frac{G_s A}{T} = \frac{0.145 \times \pi \times 12^2}{29.625} = 2.21$ K/in.

Thus, $T = 29.625 \text{ in.} = 79 @ 3/8''$

$$S = \frac{D}{4t_i} = \frac{24}{4 \times 0.375} = 16 \quad \therefore \text{OK}$$

$$\left.\begin{array}{l} E = 4G = 580 \text{ psi} \\ k = 0.57 \end{array}\right\} \; \underbrace{E_c}_{\text{COMPRESSION}} = E(1 + 2kS^2) = 169.8 \text{ ksi}$$

STRAINS

$$\epsilon_{sh} = \frac{d_i}{T} = \frac{19.13}{29.625} = 0.646 \qquad \therefore \text{SHEAR}$$

$$\left\{\begin{array}{l} \epsilon_{sc} = \dfrac{6SP}{A_r E_c} = \dfrac{6 \times 16 \times 140.6}{48.1 \times 169.8} = 1.653 \qquad \therefore \text{COMPRESSION} \\ A_r = 48.1 \text{ in}^2 \end{array}\right.$$

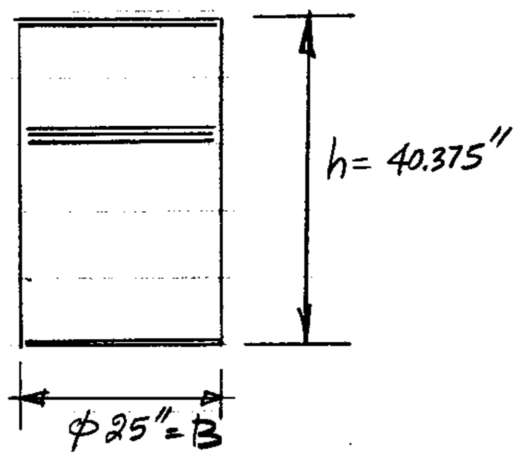
$$\epsilon_{sr} = \frac{B^2 \theta}{2 t_i T} = \frac{25^2 \times 0.01171}{2 \times 0.375 \times 29.625} = 0.329$$

$(B = 24'' + 1'')$

$$\epsilon_{TOTAL} = 2.628 = 0.48\,\epsilon_u < 0.75\,\epsilon_u \quad \therefore \text{OK}$$

STABILITY

79 RUBBER LAYERS @ 3/8"	= 29.625"		
78 STEEL PL @ 1/8"	= 9.750"	} SUBJECT TO	
1/2" END PLs	= 1.000"	} CHECK	
	h = 40.375"		



GRAVITY LOAD
140.6 kips

This design is totally unacceptable. A simple check shows that the displacement at overturning is $U_{CR} = \dfrac{F_V B}{F_V + K_{eff} \cdot h} = 13.9$ in.
$\left(F_V = 0.8D - \underset{\sim}{E}^{\approx 0} = 0.8 \times 140.6 = 112.5^{K} \text{ kips}, \; K_{eff} = 2.21 \text{ K/in.} \right)$

Thus, the bearing is unstable. The problem is clear: Strain is not a concern. Rather, stability governs. The obvious solution is to significantly enhance damping in order to reduce displacements.

5. DESIGN OF LEAD-RUBBER BEARING SYSTEM

Lead-rubber bearings exhibit bilinear hysteretic behavior as illustrated in Figure 4. For preliminary design purposes the following may be assumed:

Characteristic Strength

$$Q = A_p \sigma_{YL} \tag{7}$$

A_p = area of lead plug, σ_{YL} = effective yield stress of lead

Post-yielding Stiffness

$$K_d = f K_r = f \frac{G A_{ru}}{T} \tag{8}$$

G = shear modulus of rubber, T = rubber thickness, A_{ru} = bonded rubber area and $f = 1.1$ to 1.6 depending on conditions.

Initial Stiffness

$$K_u = 6.5 K_d \tag{9}$$

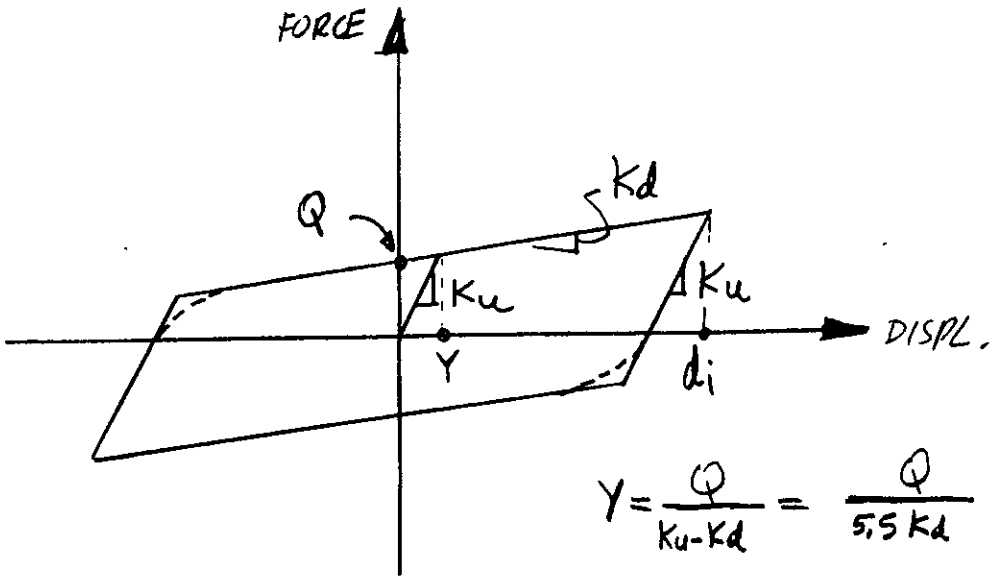


FIGURE 4 Characteristics of Lead-Rubber Bearings

Table 1 presents experimental results of a number lead-rubber bearings. The results reveal properties which are useful in design. Typical values of properties of the low damping natural rubber used in Lead-rubber bearings (hardness shore A 55) are

$$G = 100\,psi\ ,\ E = 400\,psi\ ,\ \kappa = 0.65,\ EB = \epsilon_u = 5.5 \qquad (10)$$

Furthermore based on Table 1,

$$\sigma_{YL} = 8.5\,MPa = 1230\,psi,\ f = 1.10 \text{ to } 1.15 \qquad (11)$$

provided that $S \geq 10$, bearing pressure $\geq 725\,psi$ and lead diameter $\geq 4\,in\,(100\,mm)$.

Table 1 Properties of Lead-Rubber Bearings Under Warm Conditions (Rubber Shear Modulus from Small Specimen Tests = 0.8 MPa).

Bearing Size (mm)	Rubber Thickness Σt (mm)	Shape Factor	Bearing Height (mm)	Lead Plug Dia. (mm)	Bearing Pressure (MPa)	Properties			
						G (MPa)	K_d/K_r	K_u/K_d	σ_{yl} (MPa)
230 x 180	4 @ 10	4.8	85.6	50	4.96	0.645	1.60	6.54	7.63
230 x 180	7 @ 10	4.8	125.2	50	4.96	0.643	1.59	6.51	7.63
230 x 180	10 @ 10	4.8	164.8	50	4.96	0.645	1.62	6.43	7.63
φ500	31 @ 6	20	324	100	4.93	0.889	1.13	N.A.	8.57
φ550	31 @ 6	22	324	110	6.87	0.830	1.14	N.A.	9.01
φ650	24 @ 10	15.6	363	130	5.84	0.848	1.16	N.A.	8.40
φ700	24 @ 10	16.8	363	140	6.10	0.871	1.11	N.A.	8.52
φ750	24 @ 10	18	363	150	6.70	0.892	1.11	N.A.	8.48
φ800	24 @ 10	19.2	363	160	6.50	0.896	1.09	N.A.	8.76

1000 psi = 6.91 MPa

These properties are valid for fresh rubber, scragged conditions and temperature of about 70°F (20°C). Low damping rubber exhibits small differences between unscragged and scragged conditions.

The design of lead-rubber bearings is complicated and requires the use of an iterative procedure. Let assume that all bearings will be of the same diameter. A number of them, N, will be fitted with lead plug of area A_p. The rest, M in number, will be plain bearings of bonded rubber area A. Then

$$\Sigma K_{eff} = N f \frac{G A_{ru}}{T} + N \frac{A_p \sigma_{YL}}{d_i} + M \frac{GA}{T} \qquad (12)$$

$$A_{ru} = A - A_p \qquad (13)$$

$$T_e = 2\pi \sqrt{\frac{W}{g \Sigma K_{eff}}} \qquad (14)$$

$$C_s = \frac{\Sigma K_{eff} d_i}{W} \qquad (15)$$

$$\beta = \frac{W_d}{2\pi \sum K_{eff}\, d_i^2} \;, \quad W_d = 4Q_T\,(d_i - Y) \tag{16}$$

$$Q_T = N A_p \sigma_{YL} \tag{17}$$

To arrive at a design, we start by assuming $\beta = 0.30$. Therefore, $B = 1.7$. Using Eqn. (4)

$$C_s = \frac{40\pi^2 A S_i}{g\, T_e\, B} = 0.3 \rightarrow \underline{T_e = 1.8 \text{ secs}}$$

Eqn. (1) gives $\underline{d_i = 9.53 \text{ in.}}$

Eqn. (3) gives $\sum K_{eff} = 17.74\ K/in$ ∴ REQ. STIFFNESS

Assuming $N = 10$, lead dia. $d_L = 4$ in. $\rightarrow Q_T = 154.57$ Kips

Then, Eqn. (12) gives

ASSUMED f 0.1 KSI

$$\sum K_{eff} = 17.74\ K/in. = 10 \times 1.15 \times \frac{G\pi(D^2 - d_L^2)}{4\,T} + \frac{Q_T}{d_i}$$

$$\rightarrow \frac{D^2 - d_L^2}{T} = 1.684 \text{ in.} \quad \text{WITH } d_L = 4 in,\ D \geq 3 d_L$$

FOR $D = 12$ in. $\rightarrow T = 76$ in. ! $\therefore$ UNSTABLE

Obviously, a lead-rubber bearing design with ten bearings and $C_s = 0.3$ is impossible.

However, a design with four bearings as shown in Figure 3 is feasible. Again, we assume $\beta = 0.30$ and calculate $T_e = 1.8$ secs, $d_i = 9.53''$ and $\Sigma K_{eff} = 17.74$ K/in.

Eqn. (16), with assumed $Y = 0.5$ in., gives

$$\beta = 0.3 = \frac{4 Q_T (d_i - Y)}{2\pi \, \Sigma K_{eff} \cdot d_i^2} \rightarrow Q_T = 84.1 \text{ Kips} \quad \therefore \text{REQUIRED STRENGTH}$$

$$4 \text{ BEARINGS EACH } Q = 21 \text{ Kips} = \underbrace{A_p}_{\pi d_L^2/4} \overbrace{\sigma_{YL}}^{1.23 \text{ Ksi}} \rightarrow \underline{\underline{d_L = 4.66 \text{ in}}} \quad \therefore \text{OK}$$

LEAD DIA.

Eqn. (12) gives

$$\Sigma K_{eff} = 17.74 \text{ K/in.} = \frac{4 \times 1.15 \times \overbrace{0.1}^{\text{ASSUMED } f} \times \pi \times (D^2 - d_L^2)}{4\,T} + \frac{84.1}{9.53}$$

OR $$\frac{D^2 - 4.66^2}{T} = 24.67 \text{ in.}$$

⊛ FOR $D = 17$ in. → $T = 10.84$ in. ∴ OK

PRESSURE $$\frac{\text{LOAD}}{A} = \frac{562.5/4^{\text{kips}}}{\pi D^2/4} \cong 620 \text{ psi}$$ ∴ LOW. ASSUME THAT $f = 1.15$ is VALID.

SELECT

29 RUBBER LAYERS @ 3/8" = 10.875"
28 STEEL PLs @ 1/8" = 3.500 } SUBJECT TO CHECK
1/2" END PLs = 1.000

$h = 15.375$ in

$d_L = 4.66"$ ∴ LEAD DIA.
$D = 17"$ ∴ BONDED DIA.

$$S = \frac{\pi(D^2 - d_L^2)/4}{\pi D t_i} = 10.48$$ ∴ OK

STRAINS

$$\epsilon_{sh} = \frac{9.53}{10.84} = 0.879$$

$$\epsilon_{sc} = \frac{6 \times 10.48 \times 140.625}{73.91 \times 57.51} = 2.080$$

$A_{RE} \cong 73.91 \text{ in}^2$, $F_c = 0.4\left[1 + 2 \times 0.65 \times 10.48^2\right] = 57.51$ ksi

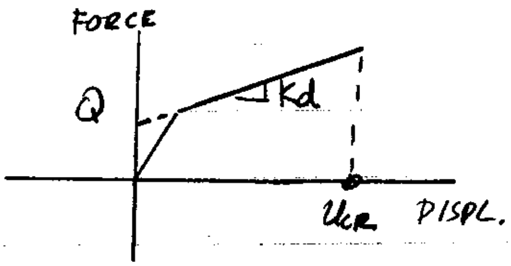
$$\epsilon_{sr} = \frac{B^2\theta}{2t_i T} = \frac{18^2 \times 0.01171}{2 \times 3/8 \times 10.875} = 0.465$$

$$\epsilon_{TOTAL} = 0.879 + 2.080 + 0.465 = 3.424 = 0.62\epsilon_u < 0.75\epsilon_u$$

$\therefore$ **OK**

OVERTURNING

$$F_v = 0.8D - \overset{0}{\underset{\sim}{E}} = 112.5 \text{ kips}, \quad B = 18 \text{ in}, \quad h = 15.375 \text{ in.}$$



$$u_{cr} \approx \frac{F_v B - Qh}{F_v + K_d h} = 11.61 \text{ in.}$$

(FOR DOWELLED BEARING)

$$Q = 21 \text{ kips}, \quad K_d = f \frac{G A_{ru}}{T} = 2.22 \text{ k/in}$$

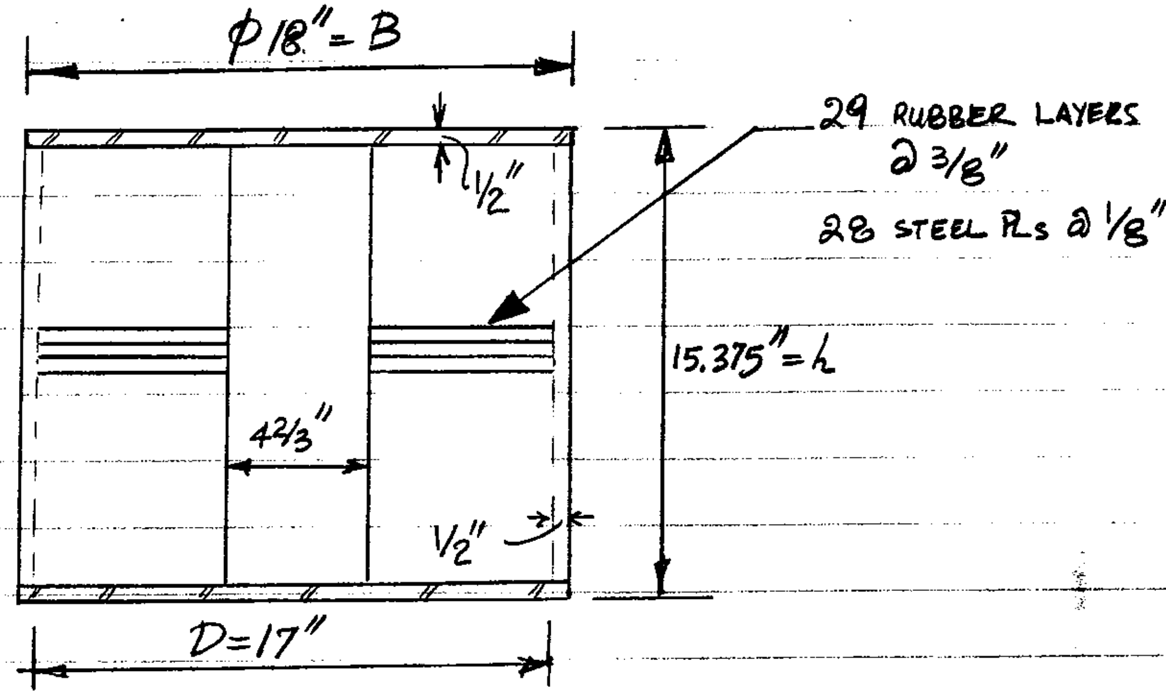
In accordance to Section 12.3 and 13 of the 1991 AASHTO Guide Specs., the bearing must be stable to displacement of $1.5 d_i$. This is an excessive requirement when considering the level of seismic loading used. It is more reasonable to require $1.25 d_i$, which is consistent with the 1994 UBC and the 1994 NEHRP provisions.

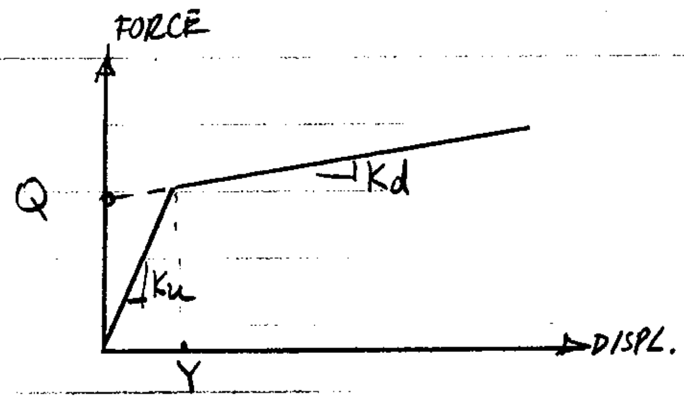
Thus, $1.25 d_i = 1.25 \times 9.53 = 11.91$ in. $\therefore$ WITHOUT CONSIDERING TORSION

As shown by elementary analysis, the bearing may be unstable. However, testing may demonstrate that the bearing is stable at $1.25 d_i$.

While the designed lead-rubber bearing is close to being unstable, the example demonstrated the significance of damping. In comparison to high damping rubber bearings (with $\beta = 0.10$ to 0.15), which could not be designed for this application, lead-rubber bearings may achieve much higher damping ($\beta \approx 0.30$ in this design), which reduces bearing displacement. The obvious benefit of reduced displacement is that of stability of the bearing. The second benefit is reduced demand for displacement capacity from the expansion joints.

More refined calculations for the designed lead-rubber bearing follow.





<u>EACH BEARING</u>

$K_d = 1.15 \dfrac{G A_{ru}}{T} = 2.22\ K/in$

$K_u = 6.5\,K_d = 14.43\ K/in$

$Q = 21\ Kips$

$Y = \dfrac{Q}{K_u - K_d} = 1.72\ in.$

FOR $d_i = 10.2'' \rightarrow \Sigma K_{eff} = 17.12\ K/in. \rightarrow T_e = 1.832\ secs$

$$\beta = \frac{4\,(4Q)\,(d_i - Y)}{2\pi \cdot \Sigma K_{eff} \cdot d_i^2} = 0.255 \rightarrow B = 1.61$$

$$d_i = \frac{10\,A\,S_i\,T_e}{B} = 10.2\ in. \quad \therefore OK$$

$$C_s = \frac{\Sigma K_{eff} \times d_i}{W} = 0.31 \approx 0.3 \quad \therefore OK.$$

6. DESIGN OF FPS BEARING SYSTEM

FPS bearings and, in general, sliding isolation bearings are ideal for applications in bridges with light loads. They are inherently stable and very easy to design.

FPS bearings (see NCEER Report 93-0020) are characterized by a lateral force-displacement relation

$$F = \frac{W}{R} d_i \pm f_{max} W \qquad (18)$$

where f_{max} = coefficient of friction at high velocity of sliding and R = radius of curvature. Typical frictional properties of FPS bearings are shown in Figure 5 and 6.

For FPS bearings, the effective period and damping ratio are easily shown to be

COMPOSITE ⊥ (see NCEER Report No. 93-0020

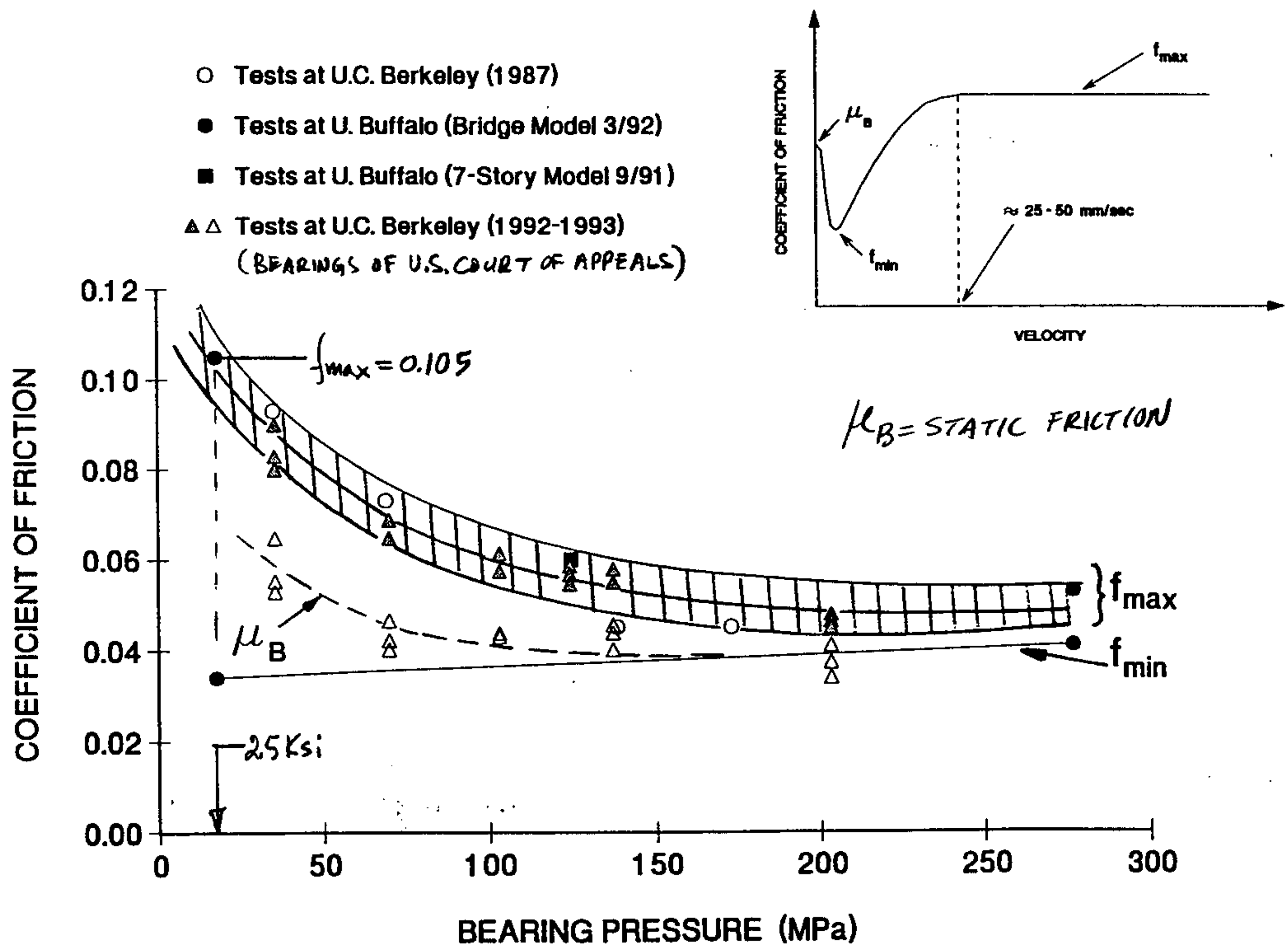


FIGURE 5. Frictional Properties of FPS Bearings

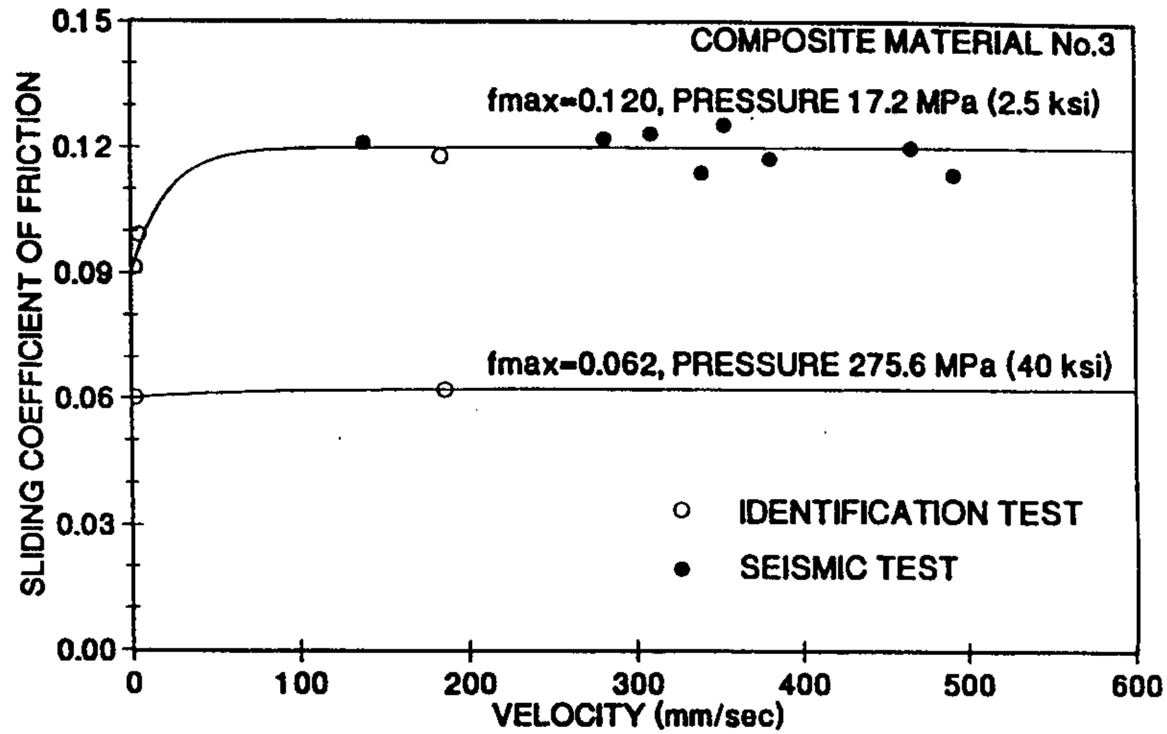


FIGURE 6 Frictional Properties of FPS Bearings (see Report NCEER 93-0020)

$$T_e = 2\pi \sqrt{\frac{1}{\frac{f_{max}\, g}{d_i} + \frac{g}{R}}} \tag{19}$$

$$\beta = \frac{2}{\pi} \left(\frac{f_{max}}{f_{max} + \frac{d_i}{R}} \right) \tag{20}$$

The actual period of free vibration is dependent only on radius R:

$$T_b = 2\pi \sqrt{\frac{R}{g}} \tag{21}$$

We proceed with a design at bearing pressure of 2500 psi (17.3 MPa) which is below all limits speified in 1992 AASHTO. This pressure was utilized in tests of a highway bridge on the shake table (see Report NCEER 93-0020). The value of f_{max} equals 0.105 (see also Figure 5) for composite material 1 and 0.120 (see Figure 6) for composite material 3. Calculations are summarized in Table 2. We note that

$$C_s = \frac{d_i}{R} + f_{max} \tag{22}$$

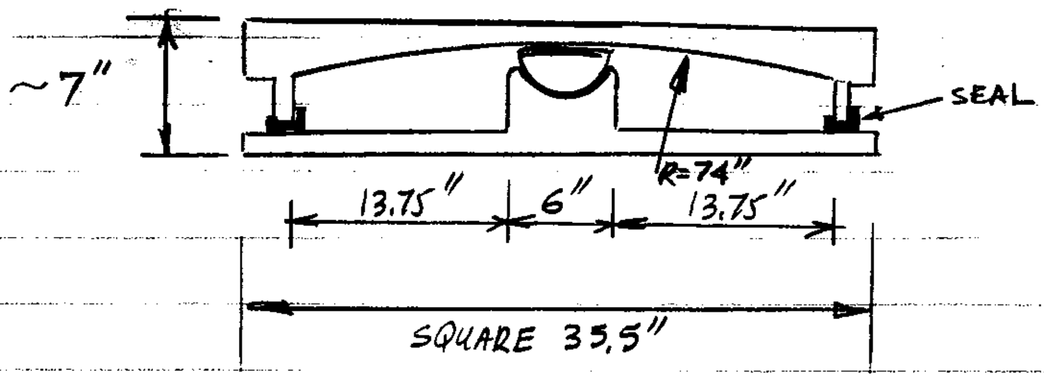
Table 2 Response of FPS Isolation System

R (in.)	T_b (secs)	f_{max}	T_e (secs)	β	B	d_i (in.)	C_s	COMMENTS
74	2.75	0.105	2.141	0.251	1.601	12.03	0.268	R USED IN BEARING OF U.S. COURT OF APPEALS
74	2.75	0.120	2.045	0.284	1.668	11.03	0.270	
74	2.75	0.15	1.893	0.348	1.795	9.29	0.275	USED B OF 1991 UBC
74	2.75	0.20	1.584	0.425	1.925	7.41	0.300	—"—
49.55	2.25	0.12	1.790	0.234	1.568	10.27	0.327	N.G.
88	3.00	0.12	2.165	0.305	1.700	11.47	0.250	DESIGN IDENTICAL TO ONE TESTED. SEE NCEER 93-0020.
61.17	2.50	0.12	1.925	0.259	1.618	10.71	0.295	

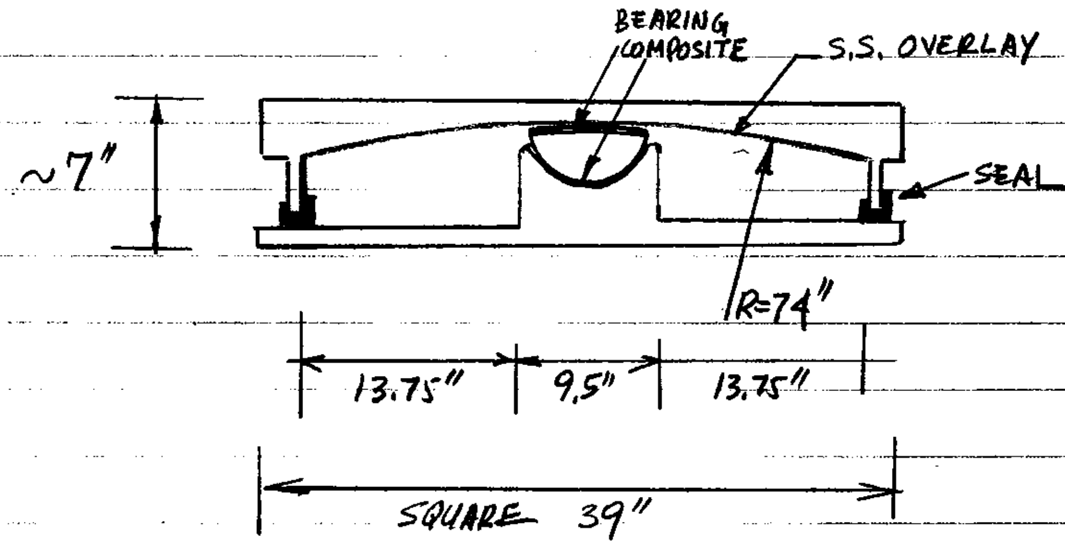
The results of this table demonstrate that a design with $f_{max}=0.20$ results in the least bearing displacement. However, to achieve friction of 0.20 requires either low bearing pressure, which leads to large bearing size, or the use of a bimetallic interface, which is unreliable in its long-term properties.

We proceed in selecting a design with $f_{max}=0.12$ and $R=74$ in. It results in $d_i=11.03$ in. and $C_s=0.27$, which is within the design criteria. Not only the design is entirely feasible, it is also highly reliable. An increase of friction by 67% (from 0.12 to 0.20), which is highly improbable, results in a shear force coefficient still within the design criteria.

Designs of FPS bearings with displacement capacity equal to $1.25\ d_i$ are shown in Figure 7.



DESIGN FOR LOAD OF 56.25 kips (10 BEARINGS)



DESIGN FOR LOAD OF 140.625 kips (4 BEARINGS)

FIGURE 7 Design of FPS Bearings

The designed FPS bearing for the 10-bearing configuration is nearly square 36×36 in. Installation of the bearing below the 16.5 in. wide W36×245 girder requires extension of the flange by 9.5 in. on both sides and the use of stiffeners. Thus, installation is difficult. However, the designed bearing for the 4-bearing configuration is easily installed.

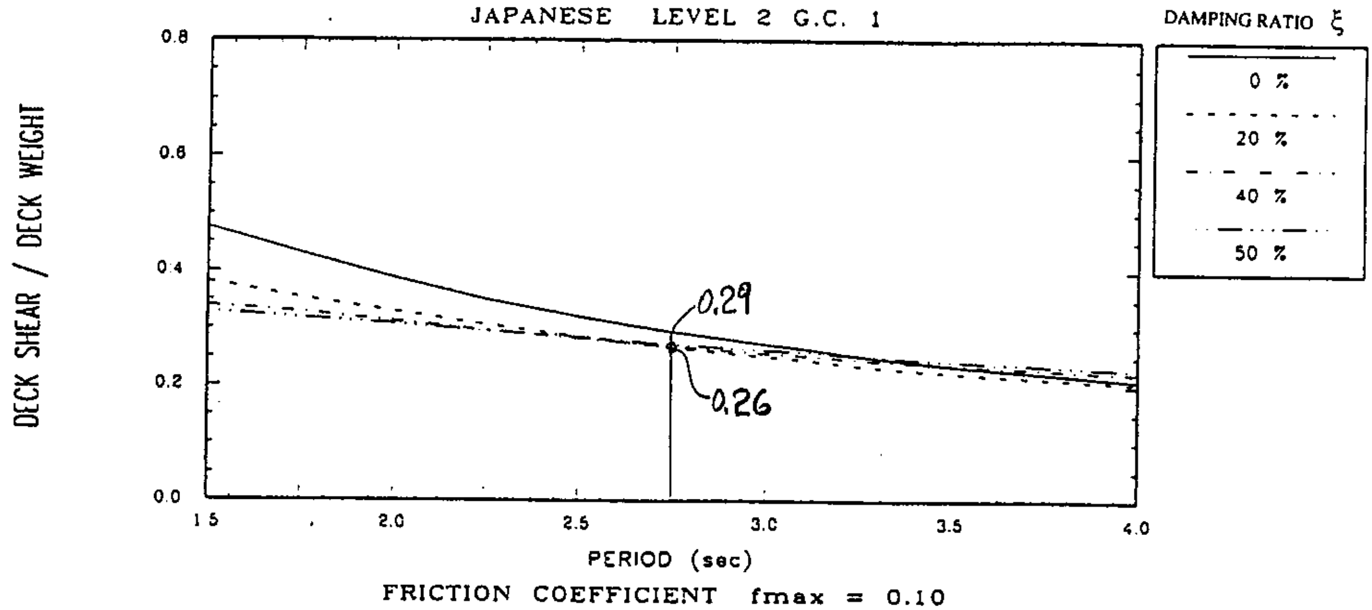
Of interest is to note the small height of the FPS bearings. At about 7 in. tall, the bearing is ideal for replacement of existing rocker or roller bearings.

7. DESIGN OF A SLIDING ISOLATION SYSTEM WITH FLUID VISCOUS DAMPERS

Sliding isolation systems with fluid dampers have been experimentally and analytically studied by Tsopelas et al., "NCEER-Taisei Corp. Research Program on Sliding Seismic Isolation Systems for Bridges, Experimental and Analytical Study of Systems consisting of Sliding Bearings, Rubber Restoring Force Devices and Fluid Dampers," Report No. NCEER-93-xxxx.

Herein, we combine FPS bearings with fluid dampers to arrive at a practical isolation system. We utilize a design $R = 74''$, bearing pressure $= 2.5$ ksi ($f_{max} = 0.105$) and simply enhance the ability to dissipate energy by using linear viscous dampers. The added viscous damping ratio will be of the order of 50% of critical. Under these conditions the static analysis procedure of AASHTO is not applicable. We utilize dynamic analysis.

Figure 8 shows nonlinear response spectra of a simple rigid deck model of an isolated sliding bridge for the Japanese Level 2, Ground Condition 1 input. This input is approximately equivalent to the AASHTO, 0.6g, soil type II input for periods above about 1.3 secs. Figure 9 compares the Japanese Level 2 spectra to the AASHTO, 0.6g, soil type II spectrum. Evidently, in the velocity region of the spectrum the Japanese Level 2, Ground Condition 1 spectrum is slightly more conservative than the AASHTO spectrum. Thus, we use the spectra of Figure 8 for calculating the response (for details see Tsopelas et al., cited earlier).



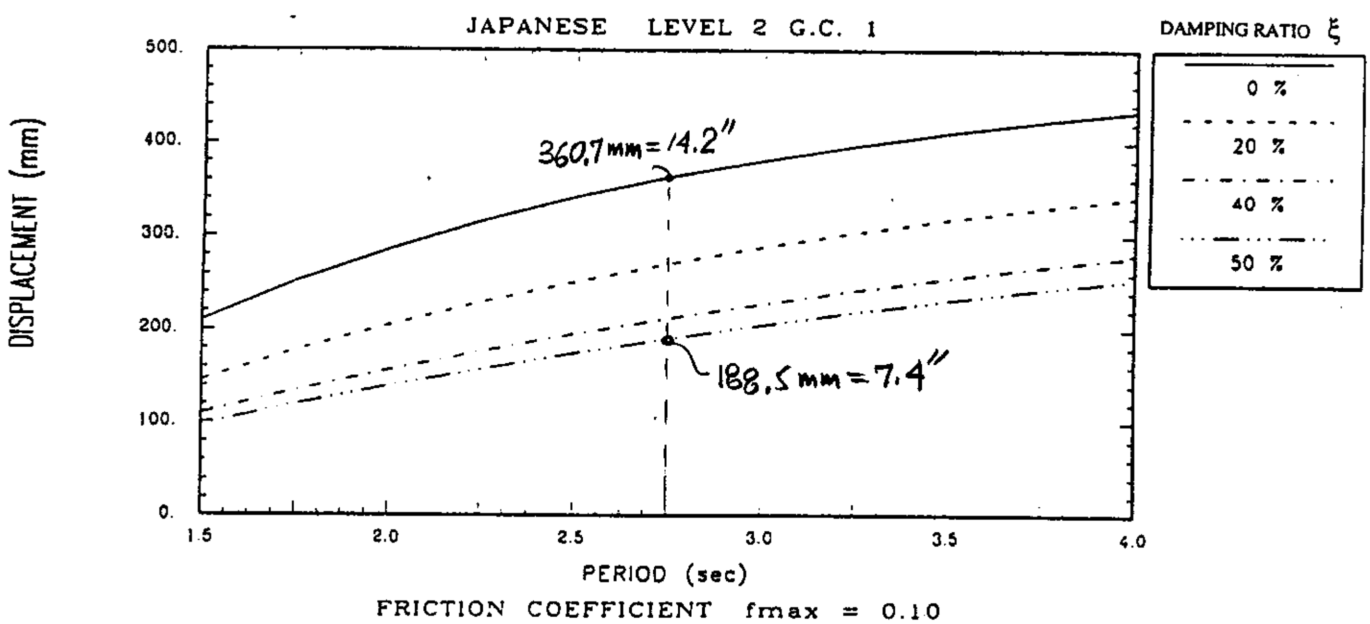


FIGURE 8 Nonlinear Response Spectra of Simplified Deck Model.

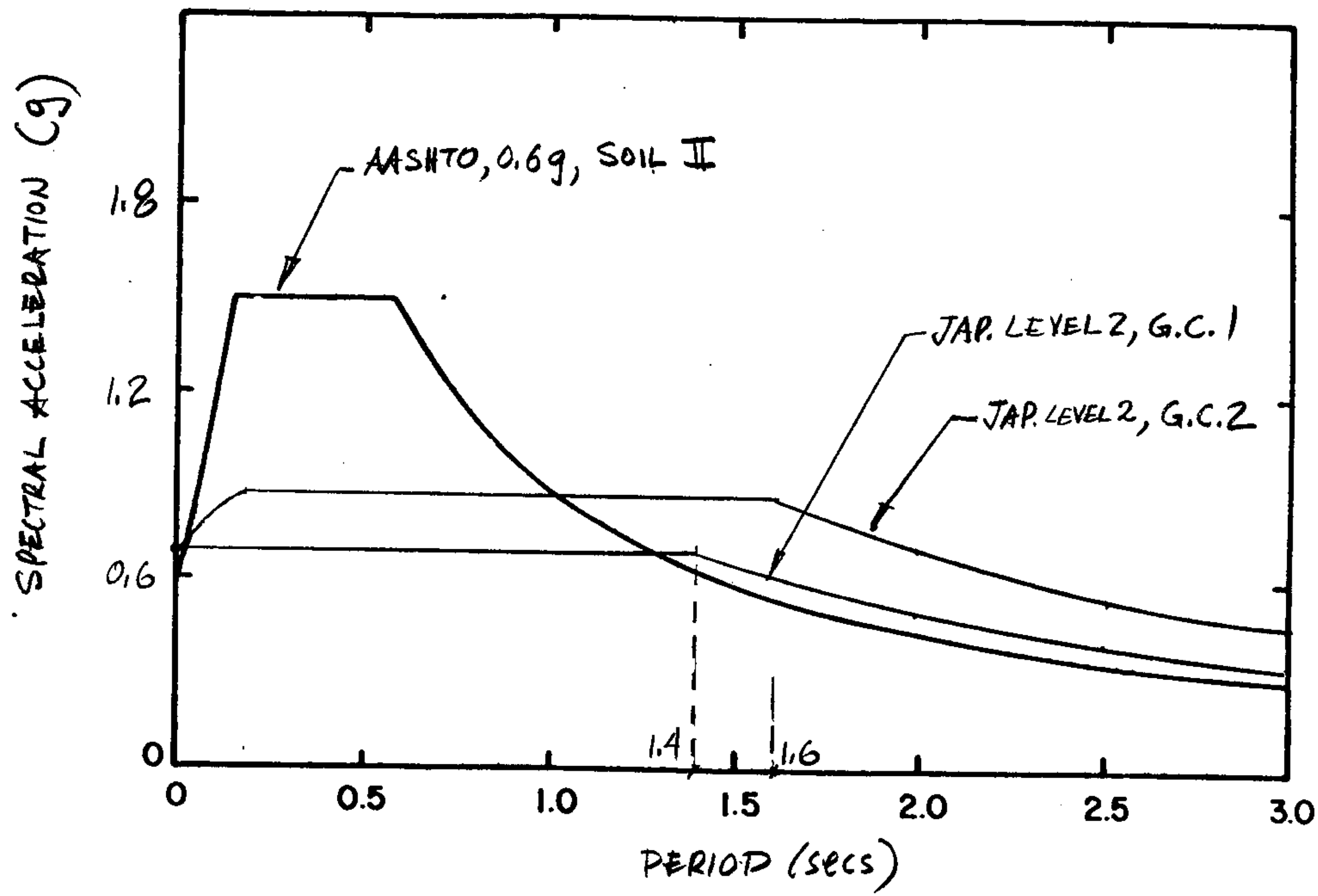
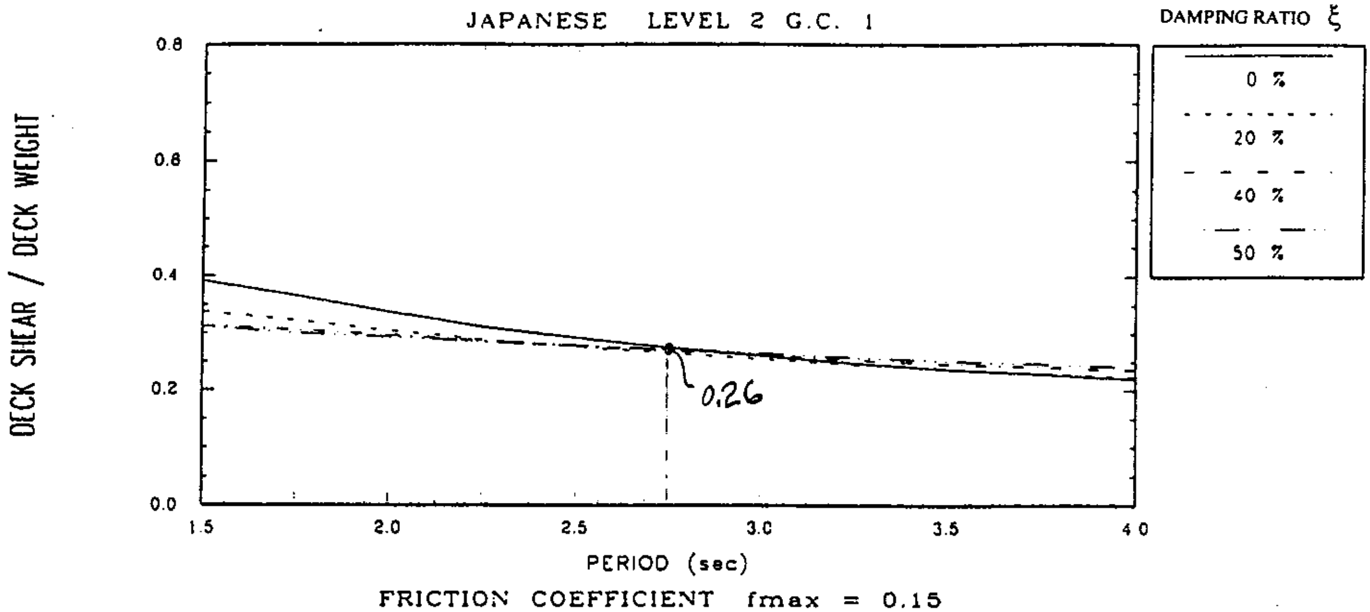


FIGURE 9 Comparison of Japanese Level 2 and AASHTO Spectra

First we verify the validity of the spectra by computing the response for $f_{max} = 0.10$, $T = 2.75$ secs and $\xi = 0$ (see Table 2). We find $C_s = 0.29$ and $d_i = 14.2''$. These compare well with $C_s = 0.27$ and $d_i = 12.0''$ computed for the AASHTO spectrum.

Selecting $\xi = 50\%$, we have $C_s = 0.26$ and $d_i = 7.4''$, which is a remarkable improvement. To demonstrate the reliability of the design, we assume that $f_{max} = 0.15$ and $\xi = 40\%$. From the spectra of Figure 10, we compute $C_s = 0.26$ and $d_i = 5.5''$. Thus, a 50% increase in friction and a 20% reduction in viscous damping result in the same coefficient C_s and even lower displacement.

Dampers to produce a damping ratio $\xi = 0.5$ must have a constant C, such that



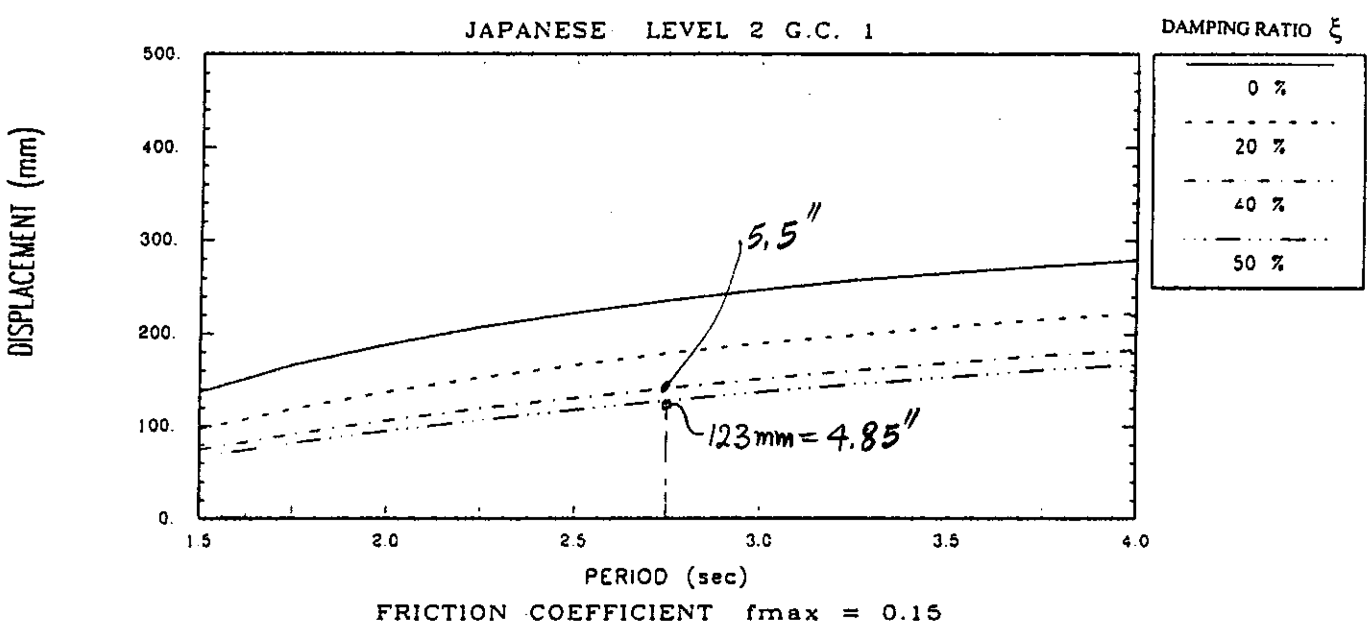


FIGURE 10 Nonlinear Spectra for fmax = 0.15

$$C = 4\pi \xi \frac{W}{gT} \tag{23}$$

where $W = 562.5$ kips, $T = 2.75$ secs. Thus, $C = 3326$ lb s/in.

Considering eight dampers placed at 45° angle (so that they are effective in both principal directions), we have

$$8\, C_o \cos^2 45° = 3326 \text{ lb s/in}$$

or $\underline{C_o = 831.5 \text{ lb s/in} \quad \text{EACH DAMPER}}$.

The displacement capacity of each damper should be

$\cos 45° \times 7.4'' = 5.23''(\times 1.25) = 6.54''$

UTILIZING 1.25 RATHER THAN 1.5 FACTOR

PEAK VELOCITY $= \frac{2\pi}{T} \times 6.54'' = 14.94$ in/sec (WITH FACTOR 1.25)

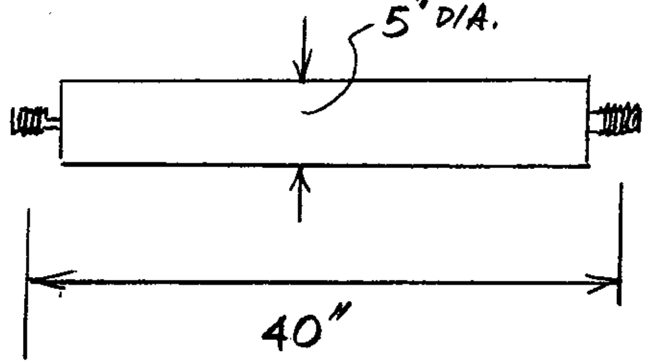
PEAK FORCE $= C_o \times 14.94 = 12.42$ kips (WITH FACTOR 1.25)

SUPPLY 8 LINEAR DAMPERS WITH $C_o = 850$ lb s/in

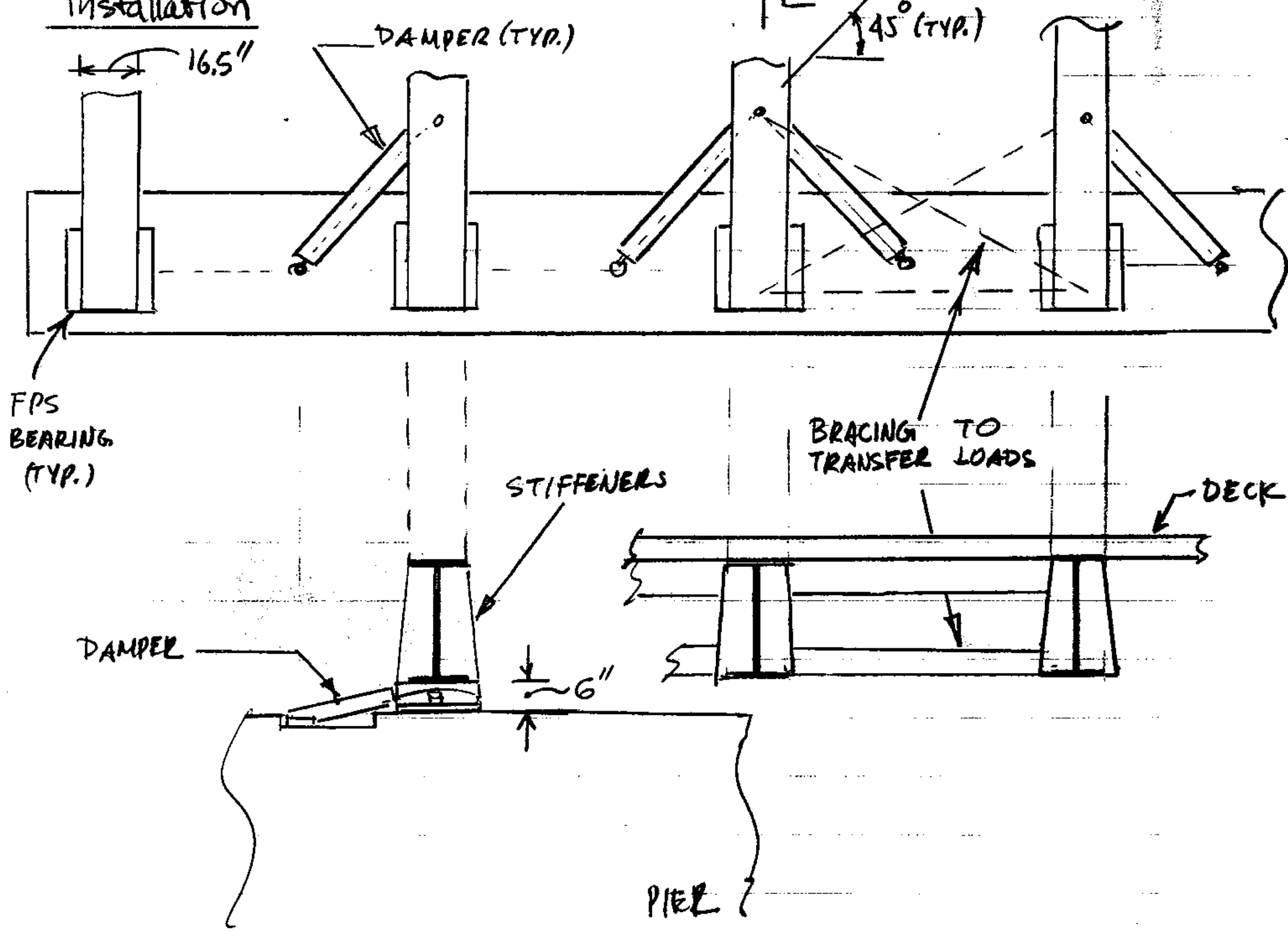
STROKE $= \pm 6.75$ in.

ULTIMATE LOAD $= 20$ kips (HAS S.F. $= 2$)

The damper approximate design is



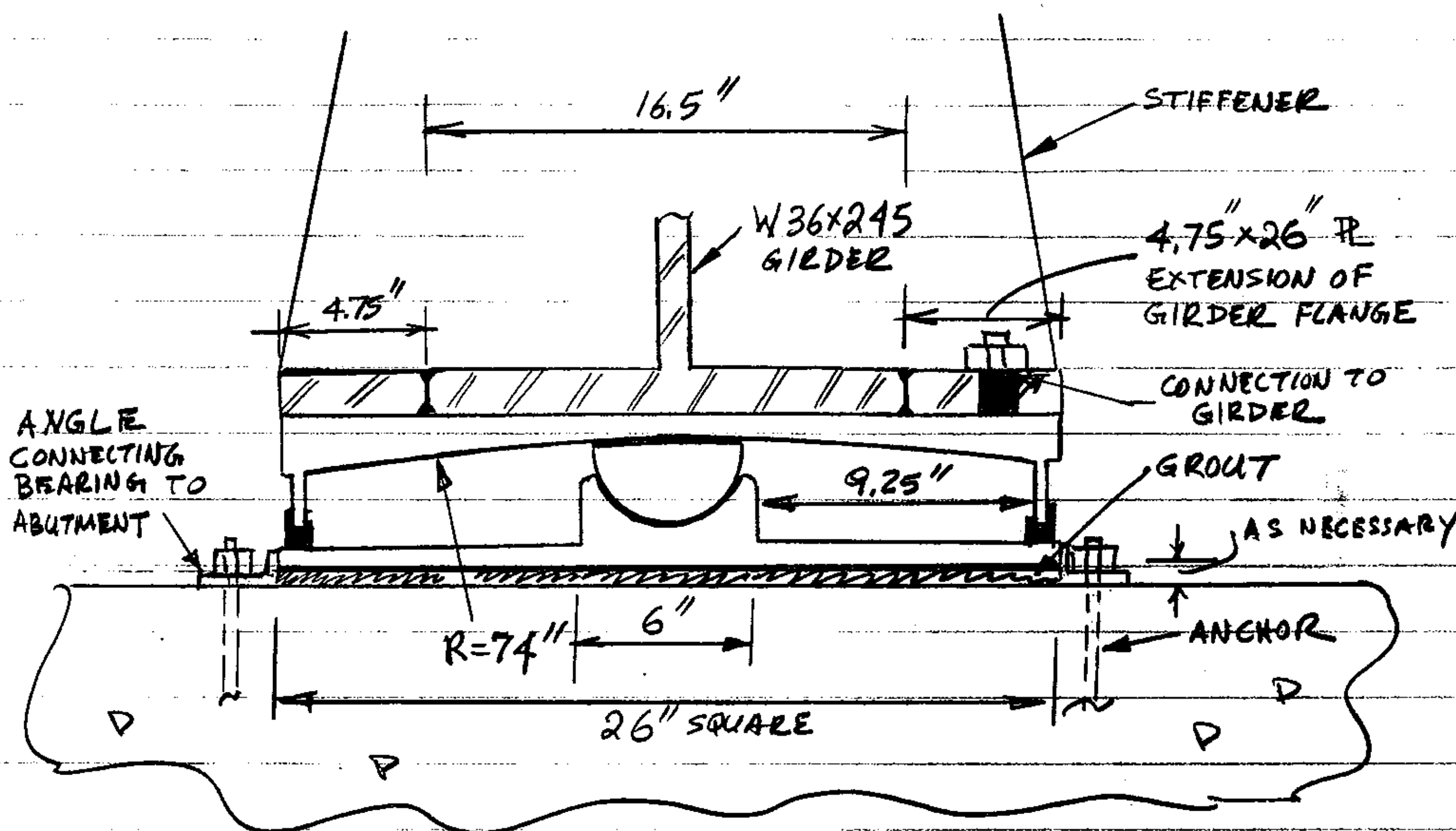
Installation

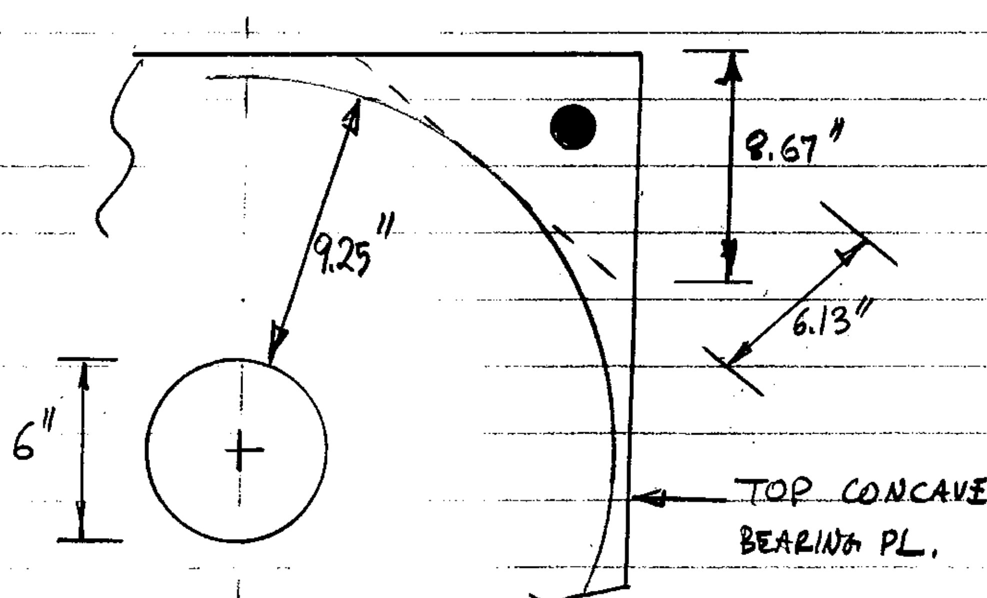


<u>BEARING INSTALLATION</u>

BEARING PRESSURE = 2.5 ksi → CONTACT DIA. = 5.4 in.

DIMENSION = $(7.4 \times 1.25) \times 2 + 6 \approx 24.5''$, SAY 26×26 in.





The design is entirely feasible. FPS bearings are now of the size that can facilitate installation. Moreover, the dampers are small with a required ultimate load of 20 Kips. The low required capacity of these dampers is the result of the low mass of the bridge and the long period of the isolation system. The resulting seismic coefficient of only 0.26 indicates that viscous damping may be further enhanced to achieve lower displacements. Furthermore, nonlinear viscous damping (of the type $F = C|\dot{u}|^{\alpha}$, $\alpha \approx 1/2$) may be utilize to further reduce displacements without significantly affecting the seismic coefficient C_s. This is the approach followed in the design of the isolation system at the San Bernardino Medical Center.

8. DESIGN OF A NATURAL RUBBER SYSTEM WITH FLUID VISCOUS DAMPERS

Fluid dampers can be very effectively combined with elastomeric bearings to produce practical designs. In this example we will utilize low damping natural rubber bearings (of the same type used for lead-rubber bearings) and fluid dampers similar to those used in the combined FPS-fluid damper system.

For the design we assume that the rubber bearings exhibit linear behavior. Furthermore, we neglect their low ability to dissipate energy ($\beta \approx 0.03$ ∴ nearly zero). To produce a design comparable to that of the FPS-viscous damper system, we use the Japanese Level 2, Ground Condition 1 motion. Figure 11 shows response spectra of this motion. The spectra demonstrate that for period in the range 2 to

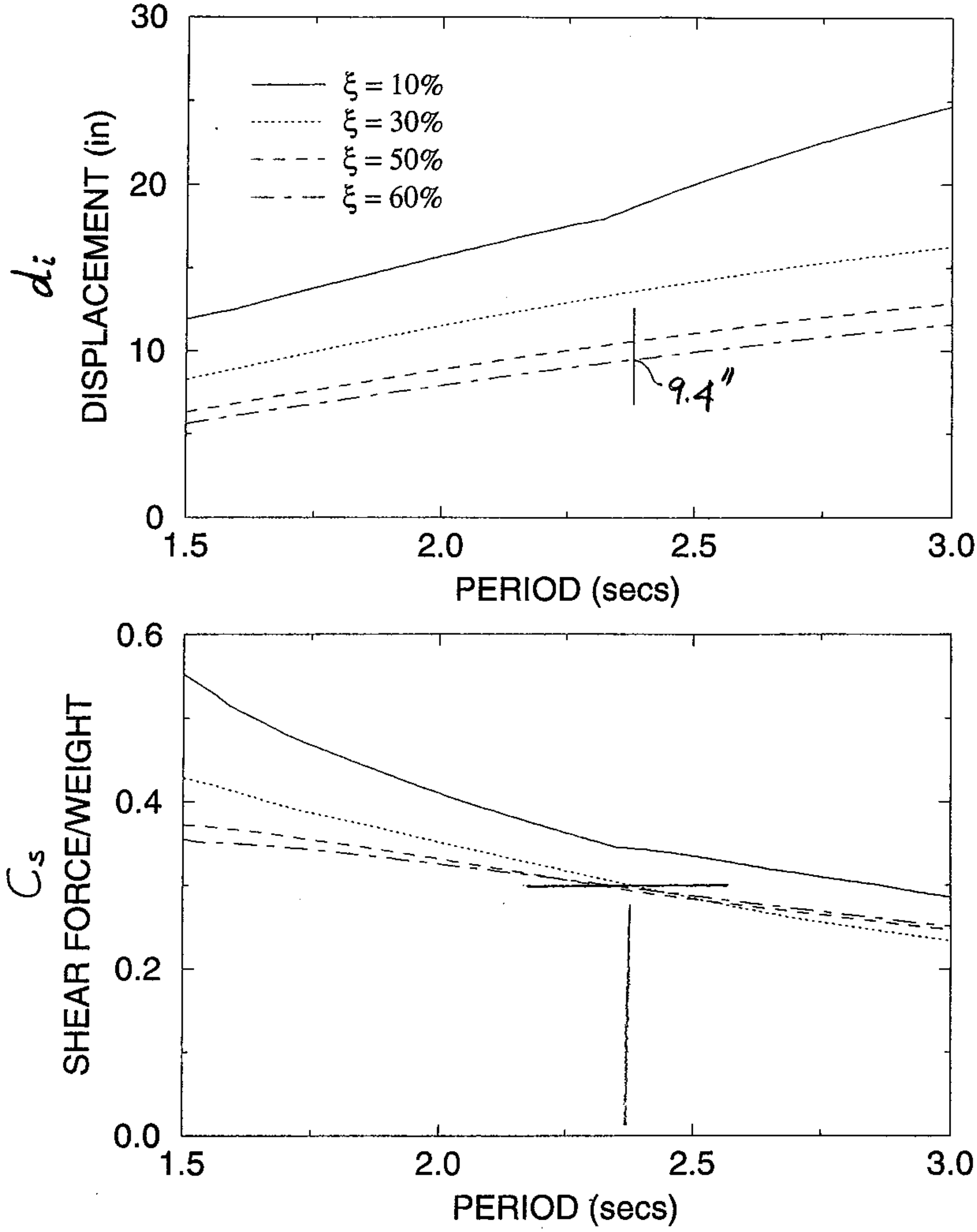


FIGURE 11 Response Spectra of Linear Elastic, Linear Viscous System for Japanese Level 2, G.C.1 Motion.

3 secs, damping has minor effect on the shear force. Thus, we attempt a design at damping ratio of 60% of critical. For $C_s \leq 0.30$, the period must be larger than about 2.4 secs. At $T = 2.4$ secs, $C_s = 0.30$ and $d_i = 9.4$ in. (note that the restoring force $K d_i / W = 4\pi^2 d_i / g T^2 = 0.167$. Thus, the dampers contribute significantly to C_s).

The required stiffness of the rubber bearings is

$$\Sigma K = \frac{4\pi^2 W}{g T^2} \qquad (22)$$

Thus, $\Sigma K = 9{,}977$ K/in.

For 10 bearings,

$$\frac{GA}{T} = \frac{9{,}977}{10} = 0.9977 \text{ K/in.}$$

For cylindrical bearings with $G = 100$ psi, $\frac{D^2}{T} = 12.70$ in.

* $T = 12$ in $\rightarrow$ $D = 12.35$ in., $A_{RR} = 16.17 \text{ in}^2$ ∴ $E_{SC} \approx 4.8$ ∴ TOO LARGE
* $T = 15$ in. $\rightarrow$ $D = 13.80$ in., $U_{CR} \approx 10$ in. ∴ UNSTABLE

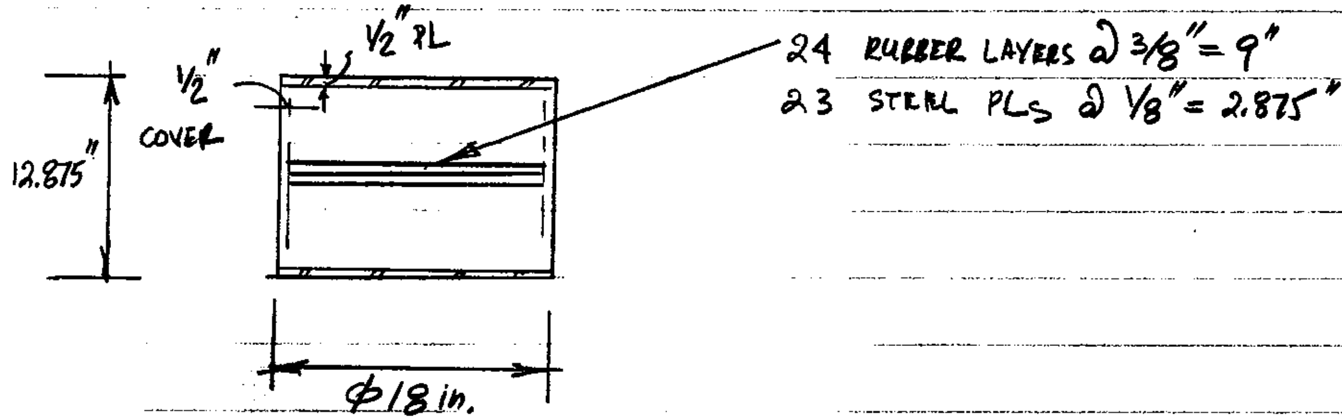
Again, the use of 10 bearings results in unstable configuration.

Trying 4 bearings,

$$\frac{GA}{T} = \frac{9.977}{4} = 2.494 \text{ K/in.}$$

Thus, $$\frac{D^2}{T} = 31.76 \text{ in.}$$

DESIGN $T = 9$ in, $D = 17$ in., 24 @ 0.375", $S = 11.33$,
$E_c = 67.2$ Ksi, $A_{RB} = 75.4 \text{ in}^2$
$\epsilon_{TOTAL} = 1.044 + 1.878 + 0.562 = 3.485$ ∴ OK
$u_{cR} = 14$ in. $\cong 1.5\, d_i$ ∴ OK.



The required damping constant in each direction is given by Eqn. (23)

$$C = 4\pi \times 0.6 \times \frac{562.5}{386.4 \times 2.4} = 4573 \text{ lb s/in.}$$

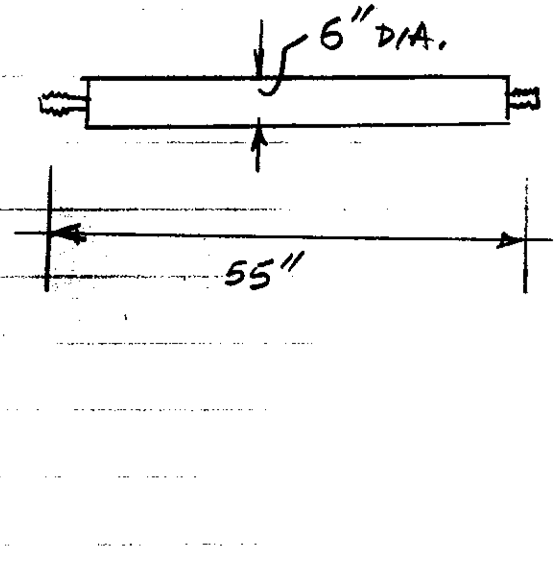
Considering eight dampers placed at 45° angle (4 dampers at each abutment as in the FPS - viscous damper system)

$$8 C_o \cos^2 45° = 4573 \text{ lbs/in}$$

or $C_o = 1143.3$ lbs/in.

DISPL. CAPACITY: $\cos 45° \times 9.4 \times (1.25) = 8.31$ in. (WITH 1.25 FACTOR)
PK. VELOCITY : $\frac{2\pi}{T} \times 8.31 = 21.75$ in/sec (-//-)
PK. FORCE : $C_o \times \dot{u} = 1143.3 \times 21.75 = 24.9$ Kips ≈ 25 Kips. (-//-)

SUPPLY 8 LINEAR DAMPERS WITH $C_o = 1145$ lbs/in.
STROKE = ±8.5 in.
ULTIMATE LOAD = 40 Kips (HAS S.F. = 2)



9. SUMMARY

To create a common basis for comparison of the designed isolation systems, dynamic analyses are performed utilizing the Japanese Level 2, G.C.1 motion. We note that this motion is slightly stronger than a realization of the AASHTO, A=0.6, soil type S2 motion. Thus, we expect slightly higher response of the lead-rubber and FPS systems, which were designed according to the 1991 AASHTO Guide Specs.

Table 3 summarizes the results of dynamic analysis. The model used in the analysis is that of a rigid deck.

Table 3 Summary of Response of Bridge Isolation Systems

ISOLATION SYSTEMS	10-BEARING CONFIGURATION 1				4-BEARING CONFIGURATION 2			
	d_i (in.)	C_s	BEAR. HEIGHT (in.)	PLAN DIM. (in.)	d_i (in.)	C_s	BEAR. HEIGHT (in.)	PLAN DIM. (in.)
HIGH DAMPING RUBBER ($\beta=0.10$)	NOT POSSIBLE				NOT POSSIBLE			
LEAD-RUBBER	NOT POSSIBLE				14.73	0.382	15.375	$\phi 18$ UNSTABLE. AT $d_i=10.2$ in. POSSIBLY STABLE
FPS $f_{max}=0.12$ $R=74$ in.	12.35	0.286	~7	35.5x35.5	12.35	0.286	~7	39x39
FPS $f_{max}=0.105$ $R=74$ in. LINEAR VISCOUS DAMPERS 3	7.18	0.271	~6	26x26 * 8 DAMPERS 5 in. DIA. 40 in. LENGTH	7.18	0.271	~6	29.5x29.5 * 8 DAMPERS 5 in. DIA. 40 in. LENGTH
FPS $f_{max}=0.105$ $R=74$ in. NONLINEAR VISCOUS DAMPERS 4	6.38	0.265	~6	26x26 * 8 DAMP. 5 in DIA. 40 in. LEN.	6.38	0.265	~6	29.5x29.5 * 8 DAMP. 5 in DIA. 40 in. LEN.
NR BEARINGS LINEAR VISCOUS DAMPERS ($\xi=60\%$)	NOT POSSIBLE				9.40	0.300	12.875	$\phi 18$ 8 DAMP. 6 in. DIA. 55 in. LEN.

1 DL = 56.25 Kips 2 DL = 140.63 Kips

3 DAMPING FORCE IN EACH PRINCIPAL DIR. $F_D = C_L \dot{u}$, $C_L = 3.4$ Ks/in. ($\xi=50\%$)

4 ——— // ——— $F_D = C_N |\dot{u}|^{1/2} \text{sgn}(\dot{u})$, $C_N = 14$ K s$^{1/2}$/in$^{1/2}$

* BEARING MAY BE MADE SMALLER