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SEISMIC RESPONSE OF BASE-ISOLATED REINFORCED CONCRETE WATER STORAGE TANKS. II: FPS ISOLATION SYSTEM

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Abstract

The analysis of the seismic response of base-isolated circular cylindrical reinforced concrete (RC) water storage tanks with lead rubber bearing (LRB) under uni- and bi-directional horizontal earthquake ground motion, described in a companion paper, is extended to frictional pendulum system (FPS). For the seismic analysis, tanks were considered to have a linear elastic behavior, the tank-water interaction was represented by an equivalent mechanical model, and the hysteretic behavior of the isolation system was represented by a bi-axial hysteretic restoring force model. The parameters of this study are: the water-height/tank-inner-radius ratio, the tank-wall-thickness/tank-inner-radius ratio, the target vibration period of the isolation system, and the friction coefficient of the isolation system. Twenty-one pairs of selected and scaled ground motions were used in time-history analysis of the case studies. The objective of this analysis was to study the effect of bi-directional ground motion as well as the effects of study parameters on seismic response of base-isolated RC water storage tanks. Seismic responses of base-isolated systems, when compared to fixed-base systems, show an effectiveness of FPS isolation system in the reduction of base shear values in the order of 71% to 92% for *H/R* = 0.5; of 84% to 97% for *H/R* = 1.0; of 92% to 99% for *H/R* = 2.0 (where *H/R* is the water-height/tank-inner-radius ratio).

Keywords: friction pendulum system, RC water storage tanks, time-history analysis

1. Introduction

The study reported here is an extension of that presented in Part I [1]. It deals with the effects of FPS isolation system on seismic response to uni- and bi-directional horizontal earthquake ground motion of circular cylindrical RC water storage tanks. The analysis is implemented considering that the value and direction of the frictional force that is mobilized during motion in this isolation system depend on the normal load, isolation system pressure, velocity of sliding, and direction of sliding. Water storage tanks play a fundamental role in the water supply system; however, they are susceptible to severe seismic events that can significantly damage their structure, causing excessive lateral displacements, wall buckling, and collapse [2]. In seismic countries such as Peru, it is very important for these structures to remain operative after a severe seismic event. In Peru, many water storage tanks are built in seismic zone 4 (Z = 0.45), soil type S_1 (V_{S30} range between 500 m/s and 1 500 m/s), and soil type S_2 (V_{S30} range between 180 m/s and 500 m/s). Z is the zone factor interpreted as the maximum horizontal acceleration at stiff soil with a 10% probability of being exceeded in 50 years, normalized by the gravitational acceleration, and V_{S30} is the average shear wave velocity in the top 30 m of the soil profile [3]. Seismic isolation techniques have shown their effectiveness to improve seismic performance of water storage tanks [4, 5]. However, there is limited research on seismic response of base-isolated tank-water systems with FPS isolation system [6] subjected to bi-directional grounds motions compatible with a normative design spectrum. It is a widespread practice to estimate seismic responses of fixed-base tank-water systems using Housner's equivalent mechanical model or one of its derivatives [5, 7, 8, 9]. The main objective of this work is to contribute to the state-of-the-art knowledge of the seismic response of RC water storage tanks supported by FPS isolation system subjected to bi-directional ground motions compatible with a normative design spectrum. The specific objectives of this work are to analyze the effects of: i) bi-directional ground motion, and ii) parameters of base-isolated tank-water system, on seismic response of base-isolated RC water storage tanks.

2. Methodology

2.1 Structural model

Fixed-base and base-isolated tank-water structural models, were used to estimate the base shear, overturning moment of the wall, vertical sloshing displacement, and lateral displacement of the tank's base, where *H*, *R* and *e* are the water height, inner radius of the tank, and thickness of the tank's wall, respectively. The total mass of water stored in the tank is represented by a series of concentrated masses producing equivalent forces and moments on the tank's walls due to horizontal ground motion during an earthquake, and the flexibility of the walls (Figs.1 and 2) was also considered [1]. The portion of the water that participates in the open surface sloshing are called convective, where k_j, c_j, h_j and u_j are the stiffness, damping, height, and lateral displacement relative to the tank's base associated to the *j*th convective mass m_j. The portion of the water that moves jointly with the tank are called impulsive, where k_0, c_0, h_0 and u_0 are the stiffness, damping, height, and lateral displacement relative to the tank's base associated to the impulsive mass m_0. Furthermore, u_b is the lateral displacement of the tank's base relative to the ground, associated to the tank's net mass m_b; $\ddot{u}_g$ is the horizontal earthquake ground acceleration; and $m_w = m_0 + \sum_{j=1}^{\infty} m_j$ is the total mass of water [5]. Finally, the total weight of the tank-water system can be expressed as $W = m_t\, g$, where $m_t = m_w + m_b$ is the total mass of the tank-water system and g is the gravitational acceleration. The following constants were considered: damping ratio ζ_w = 0.5% for the water and ζ_{RC} = 5% for the RC, modulus of elasticity E_{RC} = 21 300 MPa and Poisson's ratio ν_{RC} = 0.20 for the RC, density ρ_w = 1 000 kg/m^3 for the water and ρ_{RC} = 2 400 kg/m^3 for the RC [10]. Special care was taken to represent the tank-water system with a wide range of convective modes of vibration (*N*), so that 90% or more of the participating mass could be included. Fig. 3, shows the accumulated percentage of modal participation factors, one can notice that over 99% of the hydrodynamic motion is sufficiently covered by the first three modes (*N* = 3) for *H*/*R* ratios larger than 0.5.

Bi-axial hysteretic restoring force model were used to represent the hysteretic behavior of the isolation system [11]. Fig. 4 shows the mathematical model of the FPS isolation system. The restoring forces are $F_{bx} = (W/R_{FPS})u_{bx} + \mu\, W\, Z_{hx}$ and $F_{by} = (W/R_{FPS})u_{by} + \mu\, W\, Z_{hy}$ in the *x*- and *y*-directions, respectively, where μ is the friction coefficient of the isolation system, W is the total weight of the tank-water system, and R_{FPS} is the curvature radius of the isolation system. Furthermore, Z_{hx} and Z_{hy} represent the hysteretic components of the restoring forces, and u_{bx} and u_{by} are the lateral displacement of the tank's base relative to the ground in the x- and y-directions, respectively. This study contemplated FPS isolation system with Teflon articulated bases in contact with polished stainless steel [6]. Fig. 5 shows the range of friction coefficients, which depend on the isolation system pressure, and velocity of sliding [12, 13, 14].

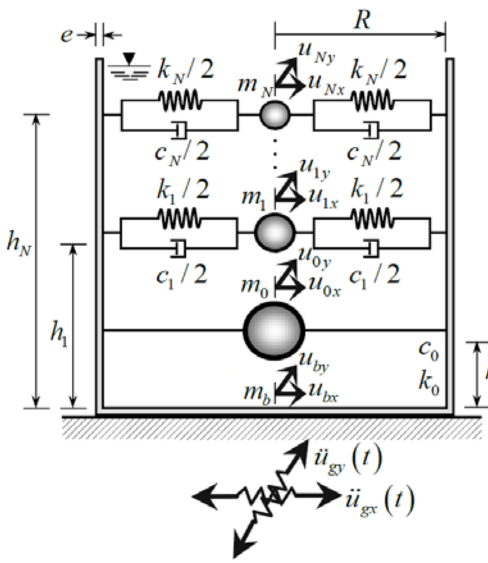

Fig. 1 – Fixed-base structural model

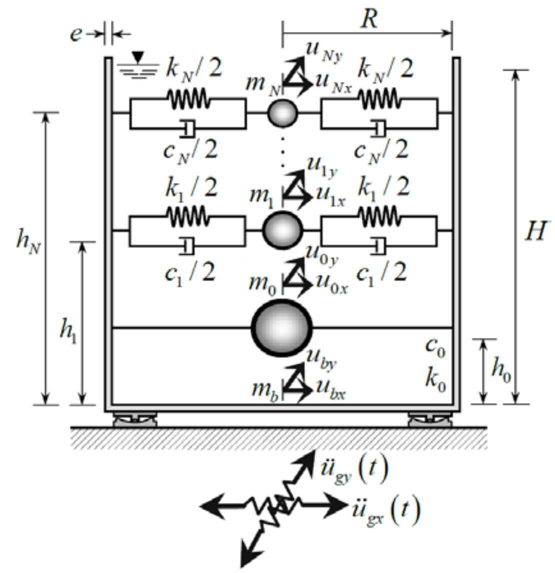

Fig. 2 – Base-isolated structural model

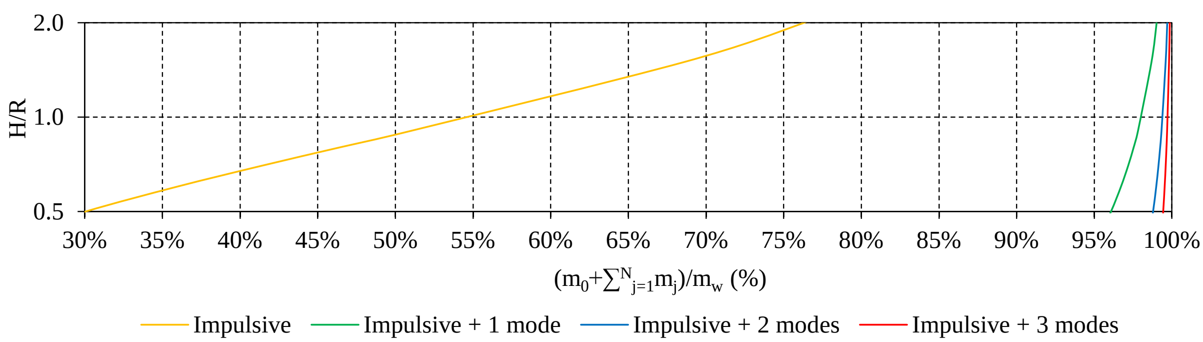

Fig. 3 Accumulated modal participation factors of the hydrodynamic system

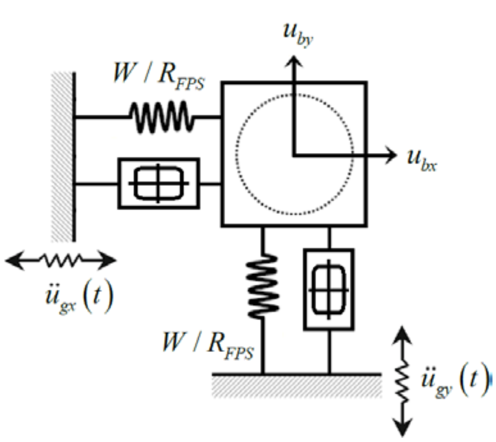

Fig. 4 – Hysteretic model of the FPS isolation system

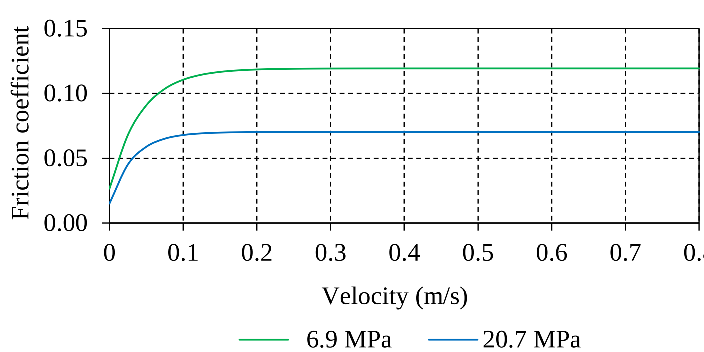

Fig. 5 – Variation of the friction coefficient with pressure and velocity

2.2 Differential equations of motion

The differential equation describing the movement of the tank-water system (superstructure) is shown in Eq. (1). This equation assumes that the tank's base behaves as a rigid diaphragm in the plane supported by isolation system, and that the base of the isolation system is in direct contact with the foundation, where **M**, **C** y **K** are the diagonal mass, damping, and stiffness matrices of the superstructure; **l** is the earthquake's influence matrix.

$$\mathbf{M}\,\ddot{\mathbf{u}} + \mathbf{C}\,\dot{\mathbf{u}} + \mathbf{K}\,\mathbf{u} = -\mathbf{M}\,\mathbf{l}\,(\ddot{\mathbf{u}}_{\mathbf{b}} + \ddot{\mathbf{u}}_{\mathbf{g}}) \tag{1}$$

Furthermore, $\ddot{\mathbf{u}}$, $\dot{\mathbf{u}}$, and $\mathbf{u}$ represent the vectors of acceleration, velocity, and displacement associated to the degrees of freedom (Figs. 1 and 2) relative to the tank's base; $\ddot{\mathbf{u}}_{\mathbf{b}}$ is the acceleration vector of the tank's base relative to the ground; and $\ddot{\mathbf{u}}_{\mathbf{g}}$ is the ground acceleration vector. The differential equation describing the movement of the tank's base for the isolated system is shown in Eq. (2), where $\mathbf{M}_{\mathbf{b}}$ is the diagonal mass matrix of the rigid tank's base.

$$\mathbf{l}^{\mathbf{T}}\,\mathbf{M}\,[\ddot{\mathbf{u}} + \mathbf{l}\,(\ddot{\mathbf{u}}_{\mathbf{b}} + \ddot{\mathbf{u}}_{\mathbf{g}})] + \mathbf{M}_{\mathbf{b}}\,(\ddot{\mathbf{u}}_{\mathbf{b}} + \ddot{\mathbf{u}}_{\mathbf{g}}) + \mathbf{f} = \mathbf{0} \tag{2}$$

Furthermore, **f** is the vector containing the non-linear restoring forces of the isolation system [15].

2.3 Parametric cases

Two parameters were used to take into account the geometrical characteristics of the tank-water system (Table 1): the ratio between the water height and the inner radius of the tank (H/R), and the ratio between the thickness of the tank's walls and the inner radius of the tank (e/R) [16]. Two parameters were used to take into account the geometrical and physical characteristics of the isolation system (Table 1): the target vibration period of the isolation system (T_b), and the friction coefficient of the isolation system (μ_b) [13]. The periods of the impulsive and convective modes of vibration corresponding to the parameters of the tank-water system are shown in [1]. The study included three types of analyses (Table 2), for a total of 6 parametric cases with fixed-base, and 72 parametric cases with base-isolated. The size of the tank's inner radius remained constant throughout the study, with a value of R = 10 m.

Table 1 – Parameters used

ID	**Tank-water**		**FPS**	
	H/R	***e/R***	T_b **(s)**	μ_b
1	0.5	0.02	2	μ_b(6.9 MPa)
2	1.0	0.04	3	μ_b(20.7 Mpa)
3	2.0	---	4	---

(---) There is no value.

Table 2 – Number of cases to be analyzed

Analysis type	**Cases**
Fixed-base (bi-directional ground motions)	6
Base-isolated (uni-directional ground motions)	36
Base-isolated (bi-directional ground motions)	36

2.4 Earthquake ground motions

A set of 21 pairs of horizontal earthquake ground motions with moment magnitude, $M_w \geq 6.5$ corresponding to soil types S_1 and S_2 were selected. The response spectra of each pair of horizontal ground motion components were scaled so that the average of the spectrum resultant (SR), defined as the square root of the sum of the squares, of the selected suite of ground-motion pairs, matches the target design spectrum for the design earthquake, in the period range from 0.01 s to 5.00 s. Design spectrum, proposed for the design of structures with seismic isolation in Peru [17], was constructed for an arbitrary location corresponding to seismic zone 4 and soil type S_2. Each pair of motions were scaled by a factor that minimizes the mean squared error (MSE) between the average SR from all horizontal component pairs and the target design spectrum (Fig. 6) [18].The characteristics of original ground motions and the scale factors are listed in Table 3.

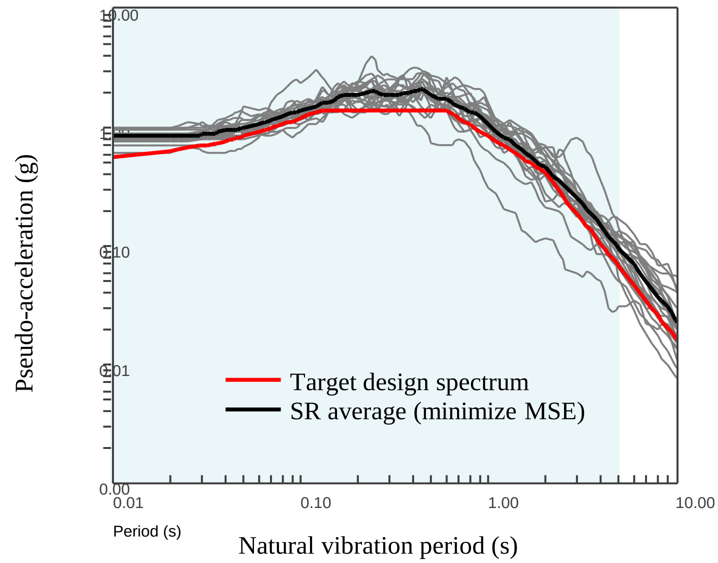

Fig. 6 – Amplitude scale average SR to minimize MSE with respect to target design spectrum (5% damping ratio)

Table 3 – Selected earthquake ground motions and their scale factors

ID	Earthquake	Year	Station	M_w	PGA^1 (g)	PGA^2 (g)	Scale factor
1	Imperial Valley-02	1940	El Centro Array #9§	6.9	0.28	0.21	2.27
2	Kern Country	1952	Taft Lincoln School§	7.3	0.18	0.16	3.68
3	Ancash	1970	Parque de la Reserva†	7.9	0.11	0.10	4.00
4	Lima	1974	Parque de la Reserva†	8.0	0.18	0.17	4.00
5	Montenegro	1979	Ulcinj-Hotel Albatros§	7.1	0.23	0.18	2.63
6	Imperial Valley-06	1979	Chihuahua§	6.5	0.27	0.25	2.36
7	Corinth	1981	Corinth§	6.6	0.30	0.24	2.58
8	Superstition Hills-02	1987	Poe Road (temp) §	6.5	0.48	0.29	1.79
9	Spitak	1988	Gukasian§	6.7	0.20	0.17	3.31
10	Loma Prieta	1989	Gilroy Array #4§	6.9	0.42	0.22	2.02
11	Cape Mendocino	1992	Centerville Beach, Naval Fac§	7.0	0.48	0.32	1.47
12	Landers	1992	Desert Hot Springs§	7.2	0.17	0.15	3.67
13	Northridge-01	1994	Canoga Park-Topanga Can§	6.6	0.39	0.36	1.50
14	Kobe	1995	Takarazuka§	6.9	0.70	0.61	0.95
15	Chi-Chi	1999	TCU072§	7.6	0.48	0.38	1.23
16	Sur del Perú	2001	César Vizcarra Vargas§	8.4	0.30	0.23	2.29
17	Chuetsu-oki	2007	Sanjo Shinbori§	6.8	0.32	0.26	2.01
18	Pisco	2007	UNICA§	8.0	0.34	0.29	1.60
19	Darfield	2010	OXZ§	7.0	0.15	0.13	4.00
20	El Mayor-Cucapah	2010	Michoacan de Ocampo§	7.2	0.54	0.41	1.22
21	Maule	2010	Constitución§	8.8	0.65	0.53	0.97

(**PGA^1**) Peak ground accelerations of component 1; (**PGA^2**) Peak ground accelerations of component 2

(†) Soil type S_1 (V_{S30} range between 500 m/s and 1 500 m/s)
(§) Soil type S_2 (V_{S30} range between 180 m/s and 500 m/s)

3. Analysis of the Results

In the present study, for uni-directional seismic excitation, the two components of selected and scaled ground motion (Table 3) were applied independently of each other. The component 1 was applied in the *x*-direction without any motion in the *y*-direction. The component 2 was applied in the *y*-direction without any motion in the *x*-direction. Finally, for bi-directional seismic excitation, the two components were applied simultaneously, where $\ddot{u}_{gx}$ and $\ddot{u}_{gy}$ are the earthquake accelerations in *x*- and *y*-directions, respectively (Figs. 1 and 2).

Fig. 7 shows the seismic response in time for the fixed-base and base-isolated systems corresponding to one case study (H/R = 1.0, e/R = 0.02; $\mu_b = \mu_b$(20.7 MPa) y T_b = 4 s) subjected to scaled ground motion from the Pisco 2007 earthquake (Table 3). S_x is the base shear in the *x*-direction, M_{yx} is the overturning moment of the walls in the *y*-direction due to forces in the *x*-direction, u_{bx} is the lateral displacement of the tank's base relative to the ground in the *x*-direction and u_{jx} is the lateral displacement of m_j relative to the tank's base in the *x*-direction. Furthermore, $d_{cx} = \sum_{j=1}^{\infty} u_{jx}\,\lambda_j\,\varepsilon_j \tanh(\lambda_j\, H/R)$ is the vertical sloshing displacement of the free water surface in contact with the tank's walls along the *x*-direction, where $\varepsilon_j = 2/(\lambda_j^2 - 1)$, λ_j is the *j*th root of $J'_1(\lambda) = 0$ and J_1 is the Bessel function of the first kind of the first order [5].

It can be appreciated that the isolation system effectively reduced the maximum base shear, the maximum overturning moment of the walls and the maximum vertical sloshing displacement; and the effect of bi-directional ground motion on seismic response of base-isolated systems is not quite significant.

The average value of the seismic responses obtained from the time-history analyses [19] was used to estimate the design seismic response associated to a case study using the 21 selected and scaled pairs of ground motions [20]. Table 4 shows the normalized design seismic responses of fixed-base systems, in the *x*-direction (bi-directional ground motions).

Table 4 – Normalized design seismic responses of the fixed-base system

Normalized response	***e/R* = 0.02**			***e/R* = 0.04**		
	***H/R* = 0.5**	***H/R* = 1.0**	***H/R* = 2.0**	***H/R* = 0.5**	***H/R* = 1.0**	***H/R* = 2.0**
S_x/W	0.263	0.512	1.089	0.315	0.482	0.954
M_{yx}/WH	0.091	0.208	0.479	0.100	0.191	0.429
d_{cx}/R	0.079	0.096	0.103	0.079	0.096	0.102

Figs. 8 and 9 shows the normalized design seismic responses of base-isolated systems, in the *x*-direction (uni- and bi-directional ground motions).

3.1 Effect of bi-directional ground motion

Disregarding the effect of bi-directional ground motion in base-isolated tank-water systems with e/R = 0.02 (Fig. 8), T_b = 2 s to 4 s, and $\mu_b = \mu_b$(6.9 MPa) to μ_b(20.7 MPa), results in the following observations:

a) The base shear is overestimated by 3% to 4% for H/R = 0.5; 2% to 4% for H/R = 1.0; and 0% to 5% for H/R = 2.0.
b) The overturning moment of the walls is overestimated by 2% to 8% for H/R = 0.5; 2% to 8% for H/R = 1.0; and 0% to 11% for H/R = 2.0.
c) The error in the lateral displacement of the tank's base varies from −4% to 1% for H/R = 0.5; −2% to 1% for H/R = 1.0; and −4% to 1% for H/R = 2.0.
d) The error in the vertical sloshing displacement varies from 1% to 9% for H/R = 0.5; 0% to 8% for H/R =

1.0; and −2% to 11% for *H/R* = 2.0.

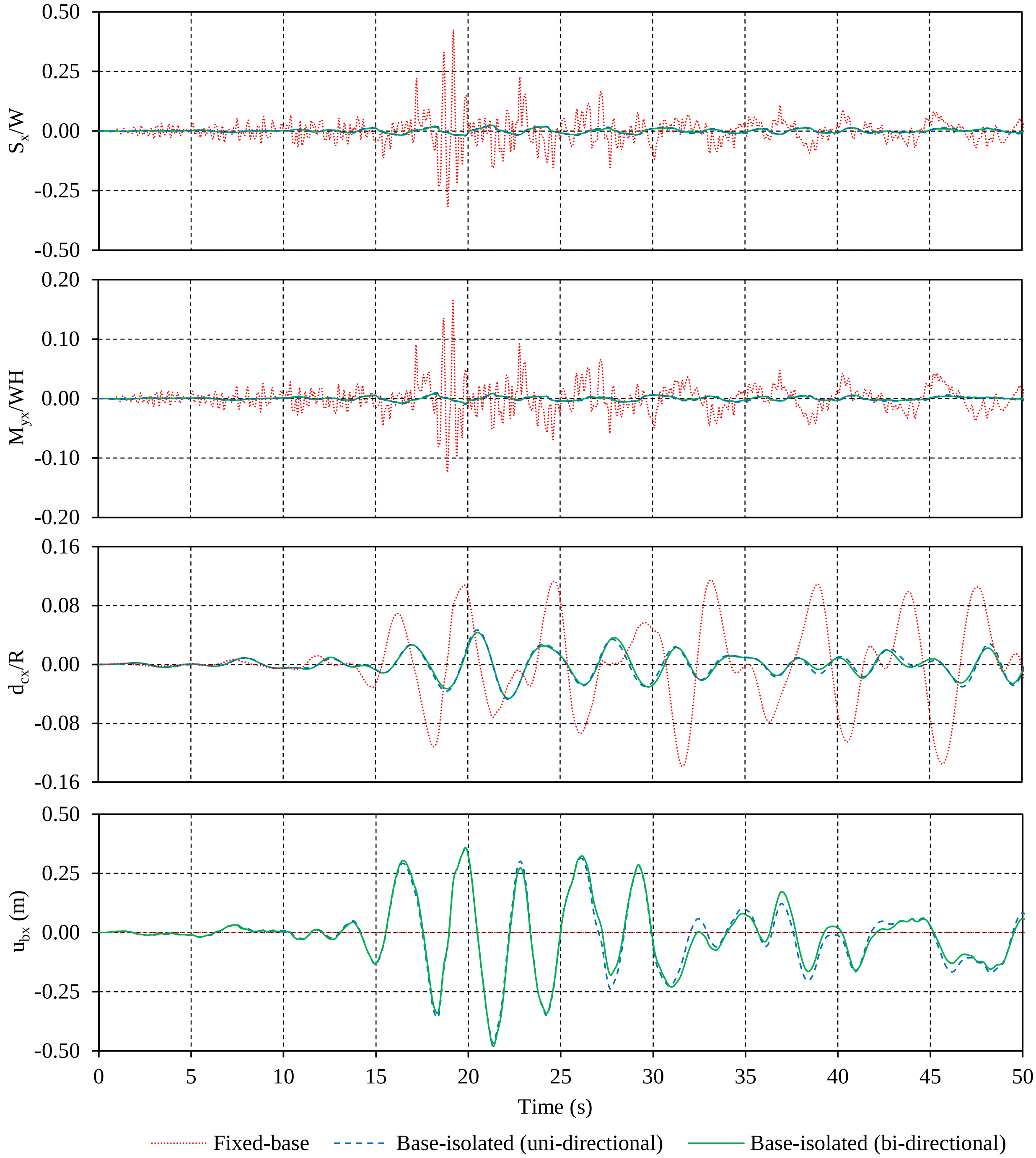

Fig. 7 – Seismic responses in time for fixed-base and base-isolated systems (H/R = 1.0, e/R = 0.02; $\mu_b = \mu_b$(20.7 MPa) and T_b = 4 s) due to Pisco 2007 earthquake (scaled ground motion)

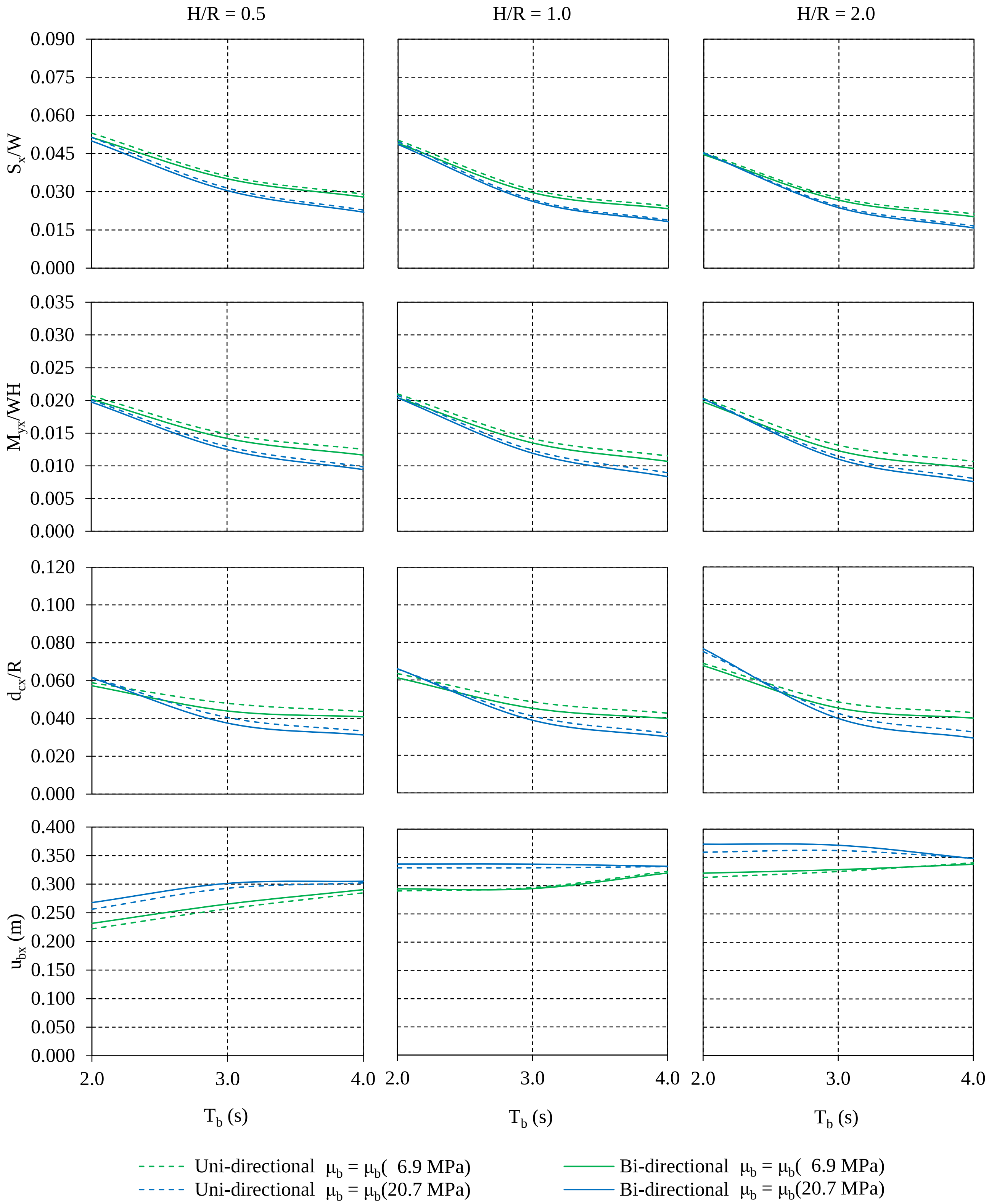

Fig. 8 – Effect of parameters T_b, and μ_b on normalized design seismic responses of base-isolated systems with e/R = 0.02; H/R = 0.5, H/R = 1.0, and H/R = 2.0

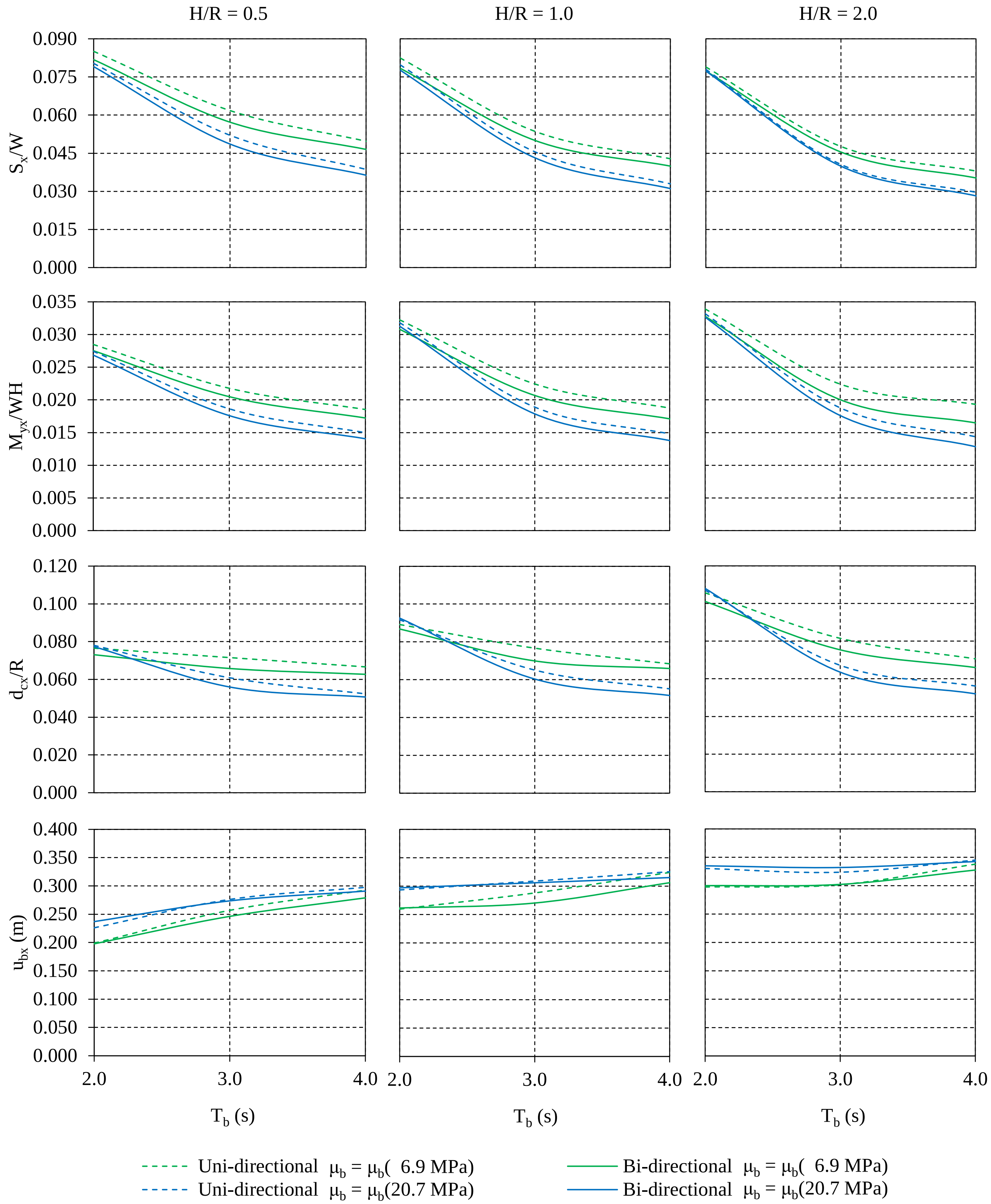

Fig. 9 – Effects of parameters T_b, and μ_b on normalized design seismic responses of base-isolated systems with e/R = 0.04; H/R = 0.5, H/R = 1.0, and H/R = 2.0

Disregarding the effect of bi-directional ground motion in base-isolated tank-water systems with *e/R* = 0.04 (Fig. 9), T_b = 2 s to 4 s, and $\mu_b = \mu_b$(6.9 MPa) to μ_b(20.7 MPa), results in the following observations:

a) The base shear is overestimated by 2% to 8% for *H/R* = 0.5; 3% to 7% for *H/R* = 1.0; and 1% to 8% for *H/R* = 2.0.
b) The overturning moment of the walls is overestimated by 2% to 8% for *H/R* = 0.5; 2% to 10% for *H/R* = 1.0; and 2% to 17% for *H/R* = 2.0.
c) The error in the lateral displacement of the tank's base varies from −5% to 5% for *H/R* = 0.5; −1% to 7% for *H/R* = 1.0; and −2% to 3% for *H/R* = 2.0.
d) The error in the vertical sloshing displacement varies from 1% to 9% for *H/R* = 0.5; −1% to 10% for *H/R* = 1.0; and −1% to 8% *H/R* = 2.0.

3.2 Effects of study parameters

The following observations can be extracted from the analysis of base-isolated tank-water systems with *e/R* = 0.02 (Fig. 8), T_b = 2 s to 4 s, and $\mu_b = \mu_b$(6.9 MPa) to μ_b(20.7 MPa):

a) The reduction in base shear when compared to the fixed-base system is 80% to 92% for *H*/*R* = 0.5; 90% to 96% for *H*/*R* = 1.0; and 96% to 99% for *H*/*R* = 2.0.
b) The reduction in overturning moment of the walls when compared to the fixed-base system is 78% to 90% for *H*/*R* = 0.5; 90% to 96% for *H*/*R* = 1.0; and 96% to 98% for *H*/*R* = 2.0.
c) The variation in vertical sloshing displacement when compared to the fixed-base system is −61% to −23% for *H*/*R* = 0.5; −69% to −31% for *H*/*R* = 1.0; and −72% to −25% for *H*/*R* = 2.0.

The following observations can be extracted from the analysis of base-isolated tank-water systems with *e/R* = 0.04 (Fig. 9), T_b = 2 s to 4 s, and $\mu_b = \mu_b$(6.9 MPa) to μ_b(20.7 MPa):

a) The reduction in base shear when compared to the fixed-base system is 74% to 88% for *H*/*R* = 0.5; 84% to 94% for *H*/*R* = 1.0; and 92% to 97% for *H*/*R* = 2.0.
b) The reduction in overturning moment of the walls when compared to the fixed-base system is 72% to 86% for *H*/*R* = 0.5; 84% to 93% for *H*/*R* = 1.0; and 92% to 97% for *H*/*R* = 2.0.
c) The variation in vertical sloshing displacement when compared to the fixed-base system is −36% to −3% for *H*/*R* = 0.5; −46% to −4% for *H*/*R* = 1.0; and −49% to 5% for *H*/*R* = 2.0.

The following observations can be extracted from the analysis of base-isolated tank-water systems with *e/R* = 0.02 to 0.04 (Figs. 8 and 9), *H/R* = 0.5 to 2.0, T_b = 2 s to 4 s, and $\mu_b = \mu_b$(6.9 MPa) to μ_b(20.7 MPa):

a) The effect of the parameter *H*/*R* variation in the normalized base shear is about 17%, in the normalized overturning moment of the walls is about 17%, in the normalized vertical sloshing displacement is about 20%, and in the lateral displacement of the tank's base is about 32%.
b) The effect of the parameter *e/R* variation in the normalized base shear is about 79%, in the normalized overturning moment of the walls is about 71%, in the normalized vertical sloshing displacement is about 78%, and in the lateral displacement of the tank's base is about 15%.
c) The effect of the parameter μ_b variation in the normalized base shear is about 22%, in the normalized overturning moment of the walls is about 22%, in the normalized vertical sloshing displacement is about 27%, and in the lateral displacement of the tank's base is about 20%.
d) The effect of the parameter T_b variation in the normalized base shear is about 65%, in the normalized overturning moment of the walls is about 62%, in the normalized vertical sloshing displacement is about 62%, and in the lateral displacement of the tank's base is about 41%.

4. Conclusions

The following research conclusions are valid for the group of parametric cases defined in Tables 1 and 2, corresponding to base-isolated tank-water systems located in seismic zone 4 and supported on soil type S_2:

1. Disregarding the effect of the bi-directional ground motion has a relatively significant effect on base shear, and overturning moment of the walls. This effect is on the order of 16% for tanks with e/R = 0.02 and 18% for tanks with e/R = 0.04.
2. Disregarding the effect of the bi-directional ground motion has a relatively insignificant effect on lateral displacement of the tank's base. This effect is on the order of 6% for tanks with e/R = 0.02 and 7% for tanks with e/R = 0.04.
3. Disregarding the effect of the bi-directional ground motion has a significant effect on vertical sloshing displacement. This effect is on the order of 31% for tanks with e/R = 0.02 and 27% for tanks with e/R = 0.04.
4. The reduction in base shear when compared to the fixed-base system is 71% to 92% for H/R = 0.5; 84% to 97% for H/R = 1.0; and 92% to 99% for H/R = 2.0.
5. The reduction in overturning moment of the walls when compared to the fixed-base system is 69% to 90% for H/R = 0.5; 83% to 96% for H/R = 1.0; and 92% to 98% for H/R = 2.0.
6. The variation in vertical sloshing displacement when compared to the fixed-base system is −62% to 1% for H/R = 0.5; −71% to −5% for H/R = 1.0; and −72% to 8% for H/R = 2.0.
7. The parameter T_b has a higher effect than the parameter μ_b, in the reduction of the base shear and overturning moment of the walls. When increasing T_b, and reducing μ_b, the isolation system becomes more effective in reducing the base shear and the overturning moment of the walls.
8. The design parameters associated to the maximum reduction of base shear are e/R = 0.02, T_b = 4 s and $\mu_b = \mu_b$(20.7 MPa). These values achieve a reduction in base shear on the order of 92% for H/R=0.5; 97% for H/R = 1.0; and 99% for H/R = 2.0.

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6. References

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