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SEISMIC RESPONSE OF BASE-ISOLATED REINFORCED CONCRETE WATER STORAGE TANKS. I: LRB ISOLATION SYSTEM

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Abstract

This paper shows 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 motions. 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 damping ratio of the isolation system, the target vibration period of the isolation system, and the strength ratio of the isolation system. Twenty-one pairs of selected and scaled ground motions were used. Time-history analysis was used 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 LRB isolation system in the reduction of base shear values in the order of 14% to 74% for H/R = 0.5; of 47% to 83% for H/R = 1.0; of 73% to 91% for H/R = 2.0 (where H/R is the water-height/tank-inner-radius ratio). The effects of frictional pendulum system (FPS) are studied in a companion paper.

Keywords: lead rubber bearing, RC water storage tanks, time-history analysis

1. Introduction

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 [1]. 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 [2].

Seismic isolation techniques have shown their effectiveness to improve seismic performance of water storage tanks [3, 4]. However, the seismic response of base-isolated tank-water systems with LRB isolation system [5] subjected to bi-directional ground motions compatible with a normative design spectrum has been limitedly researched. 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 [4, 6, 7, 8]. 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 LRB isolation system and 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. The effects of FPS isolation system, which may be quite important for base-isolated RC water storage tanks, are examined separately in a companion paper [9].

2. Methodology

2.1 Structural model

Fixed-base and base-isolated tank-water structural models (Figs.1 and 2), were used to estimate the relevant seismic responses (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.

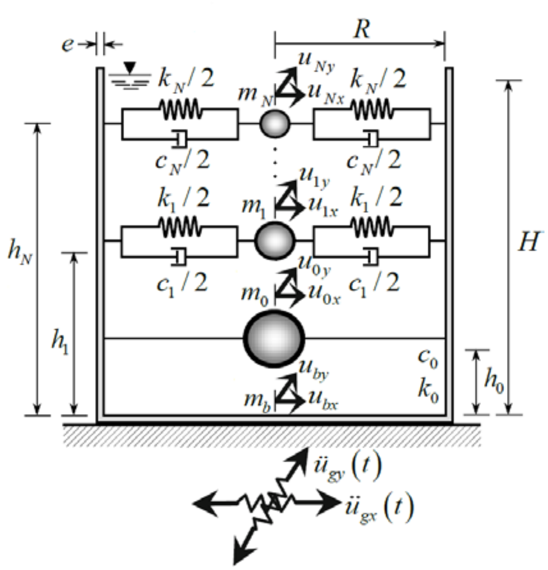

Fig. 1 – Fixed-base structural model

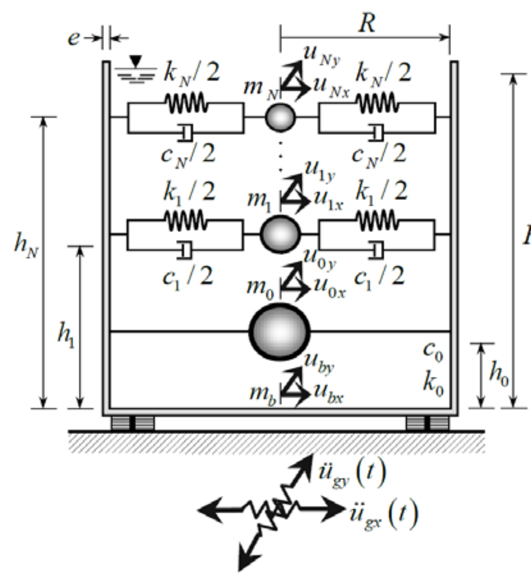

Fig. 2 – Base-isolated structural model

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 (Figs.1 and 2). 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 jth 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 $m_w = m_0 + \sum^{\infty}_{j=1} m_j$ is the total mass of water [4]. 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. To account for the flexibility of the container, the tank's walls (Figs.1 and 2) was represented by elastic shell elements [10]. The following constants were also considered in the calculations: 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 [11]. 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.

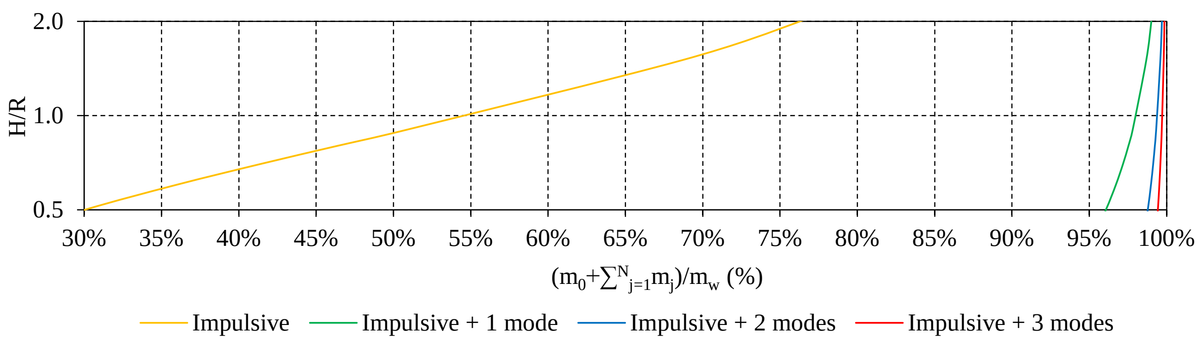

Fig. 3 Accumulated modal participation factors of the hydrodynamic system

Bi-axial hysteretic restoring force model were used to represent the hysteretic behavior of the isolation system [12]. Fig. 4 shows the mathematical model of the LRB isolation system.

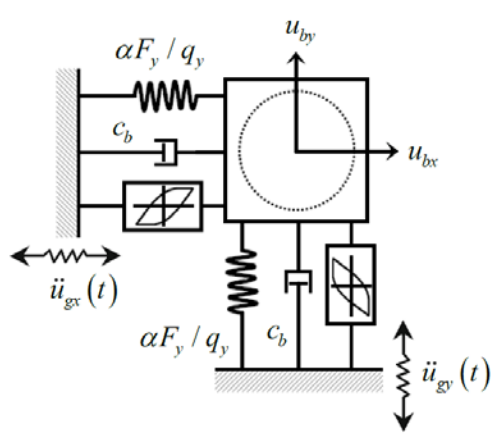

Fig. 4 – Hysteretic model of the LRB isolation system

The restoring forces of the isolation system, F_{bx} and F_{by}, in the x- and y-directions, respectively, are given by Eqs. (1) and (2), where α is the ratio of post- to pre-yielding lateral stiffness of the isolation system, F_y is the yielding strength of the isolation system.

$$F_{bx} = c_b\,\dot{u}_{bx} + \alpha(F_y/q_y)u_{bx} + (1-\alpha)F_y\,Z_{hx} \quad (1)$$

$$F_{by} = c_b\,\dot{u}_{by} + \alpha(F_y/q_y)u_{by} + (1-\alpha)F_y\,Z_{hy} \quad (2)$$

Furthermore, q_y = 0.02 m is a fixed value representing the yield displacement, Z_{hx} and Z_{hy} represent the hysteretic components of the restoring forces, 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, and c_b represent the viscous damping of the isolation system.

2.2 Differential equations of motion

The differential equation describing the movement of the tank-water system (superstructure) is shown in Eq. (3). 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.

$$\mathbf{M}\,\ddot{\mathbf{u}} + \mathbf{C}\,\dot{\mathbf{u}} + \mathbf{K}\,\mathbf{u} = -\mathbf{M}\,\mathbf{l}\,(\ddot{\mathbf{u}}_\mathbf{b} + \ddot{\mathbf{u}}_\mathbf{g}) \quad (3)$$

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. (4), where $\mathbf{M_b}$ is the diagonal mass matrix of the rigid tank's base.

$$\mathbf{l}^\mathbf{T}\,\mathbf{M}\,[\ddot{\mathbf{u}} + \mathbf{l}\,(\ddot{\mathbf{u}}_\mathbf{b} + \ddot{\mathbf{u}}_\mathbf{g})] + \mathbf{M_b}\,(\ddot{\mathbf{u}}_\mathbf{b} + \ddot{\mathbf{u}}_\mathbf{g}) + \mathbf{f} = \mathbf{0} \quad (4)$$

Furthermore, **f** is the vector containing the non-linear restoring forces of the isolation system [13].

2.3 Parametric cases

Two parameters were used to take into account the geometrical characteristics of the tank-water system: 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) [13]. Three parameters were used to take into account the geometrical and physical characteristics of the isolation system: the damping ratio of the isolation system (ζ_b), the target vibration period of the isolation system (T_b), and the strength ratio of the isolation system (F_y/W) [15].

Table 1 shows the periods of the impulsive (T_0) and convective (T_1, T_2, and T_3) modes of vibration corresponding to the parameters of the tank-water system. The study included three types of analyses, for a total of 6 parametric cases with fixed-base, and 144 parametric cases with base-isolated (Tables 2 and 3). The size of the tank's inner radius remained constant throughout the study, with a value of R = 10 m.

Table 1 – Natural periods of the impulsive and convective modes of vibration

Tank-water system parameters		**Impulsive period**	**Convective periods**		
			Mode 1	**Mode 2**	**Mode 3**
H/R	***e/R***	T_0 **(s)**	T_1 **(s)**	T_2 **(s)**	T_3 **(s)**
0.5	0.02	0.03	5.49	2.76	2.17
0.5	0.04	0.02	5.49	2.76	2.17
1.0	0.02	0.08	4.80	2.75	2.17
1.0	0.04	0.06	4.80	2.75	2.17
2.0	0.02	0.18	4.68	2.75	2.17
2.0	0.04	0.13	4.68	2.75	2.17

Table 2 – Parameters used

ID	Tank-water		LRB		
	H*/*R	***e*/*R***	ζ_b	T_b **(s)**	F_y/W
1	0.5	0.02	0.05	2	0.05
2	1.0	0.04	0.25	3	0.15
3	2.0	---	---	4	---

(---) There is no value.

Table 3 – Number of cases to be analyzed

Analysis type	Cases
Fixed-base (bi-directional ground motions)	6
Base-isolated (uni-directional ground motions)	72
Base-isolated (bi-directional ground motions)	72

2.4 Earthquake ground motions

Design codes require 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 exceed the design spectrum by a specified factor over a specified period range. 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 SR, 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 [16], 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. 5) [17].The characteristics of original ground motions and the scale factors are listed in Table 4.

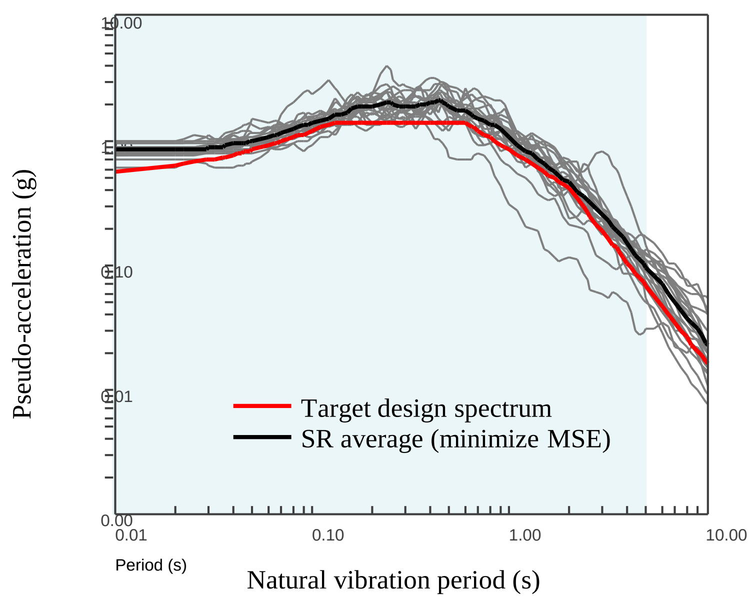

Fig. 5 – Amplitude scale average SR to minimize MSE with respect to target design spectrum (5% damping ratio)

Table 4 – 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 4) 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. 6 shows the seismic responses in time for the fixed-base and base-isolated systems corresponding to one case study (H/R = 1.0, e/R = 0.02; ζ_b = 0.25, T_b=4 s and F_y/W = 0.05) subjected to scaled ground motion from the Pisco 2007 earthquake (Table 4). 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 $\varepsilon_j = 2/(\lambda^2_j - 1)$, 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 [4].

It can be appreciated that the isolation system effectively reduced the maximum base shear and the maximum overturning moment of the walls, 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 [18] was used to estimate the design seismic response associated to a case study using the 21 selected and scaled pairs of ground motions [19]. Table 5 shows the normalized design seismic responses of fixed-base systems, in the *x*-direction (bi-directional ground motions).

Table 5 – Normalized design seismic responses of fixed-base systems

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. 7 and 8 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 to 0.04 (Figs. 7 and 8), F_y/W = 0.05 to 0.15, T_b = 2 s to 4 s, and ζ_b = 0.05 to 0.25, results in the following observations:

a) The base shear is overestimated by 3% to 7% for H/R = 0.5; 2% to 8% 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 7% for H/R = 0.5; 2% to 8% for H/R = 1.0; and 1% to 7% for H/R = 2.0.
c) The error in the lateral displacement of the tank's base varies from −1% to 6% for H/R = 0.5; −2% to 6% for H/R = 1.0; and −4% to 4% for H/R = 2.0.
d) The error in the vertical sloshing displacement varies from −1% to 5% for H/R = 0.5, −1% to 8% for H/R = 1.0; and −2% to 7% for 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 to 0.04 (Figs. 7 and 8), F_y/W = 0.05 to 0.15, T_b = 2 s to 4 s, and ζ_b = 0.05 to 0.25:

a) The reduction in base shear when compared to fixed-base systems is 21% to 74% for H/R = 0.5; 49% to 83% for H/R = 1.0; and 73% to 91% for H/R = 2.0.
b) The reduction in overturning moment of the walls when compared to fixed-base systems is 21% to 71% for H/R = 0.5; 51% to 83% for H/R = 1.0; and 75% to 91% for H/R = 2.0.
c) The variation in vertical sloshing displacement when compared to fixed-base systems is −20% to 5% for H/R = 0.5; −18% to 15% for H/R = 1.0; and −9% to 27% 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. 7 and 8), H/R = 0.5 to 2.0, F_y/W = 0.05 to 0.15, T_b = 2 s to 4 s, and ζ_b = 0.05 to 0.25:

a) The effect of the parameter e/R variation in the normalized base shear is about 8%, in the normalized overturning moment of the walls is about 6%, in the normalized vertical sloshing displacement is about 6%, and in the lateral displacement of the tank's base is about 18%.
b) The effect of the parameter H/R variation in the normalized base shear is about 18%, in the normalized overturning moment of the walls is about 33%, in the normalized vertical sloshing displacement is about 38%, and in the lateral displacement of the tank's base is about 38%.
c) The effect of the parameter ζ_b variation in the normalized base shear is about 20%, in the normalized overturning moment of the walls is about 18%, in the normalized vertical sloshing displacement is about

13%, and in the lateral displacement of the tank's base is about 40%.

d) The effect of the parameter T_b variation in the normalized base shear is about 58%, in the normalized overturning moment of the walls is about 57%, in the normalized vertical sloshing displacement is about 24%, and in the lateral displacement of the tank's base is about 48%.

e) The effect of the parameter F_y/W variation in the normalized base shear is about 99%, in the normalized overturning moment of the walls is about 92%, in the normalized vertical sloshing displacement is about 18%, and in the lateral displacement of the tank's base is about 43%.

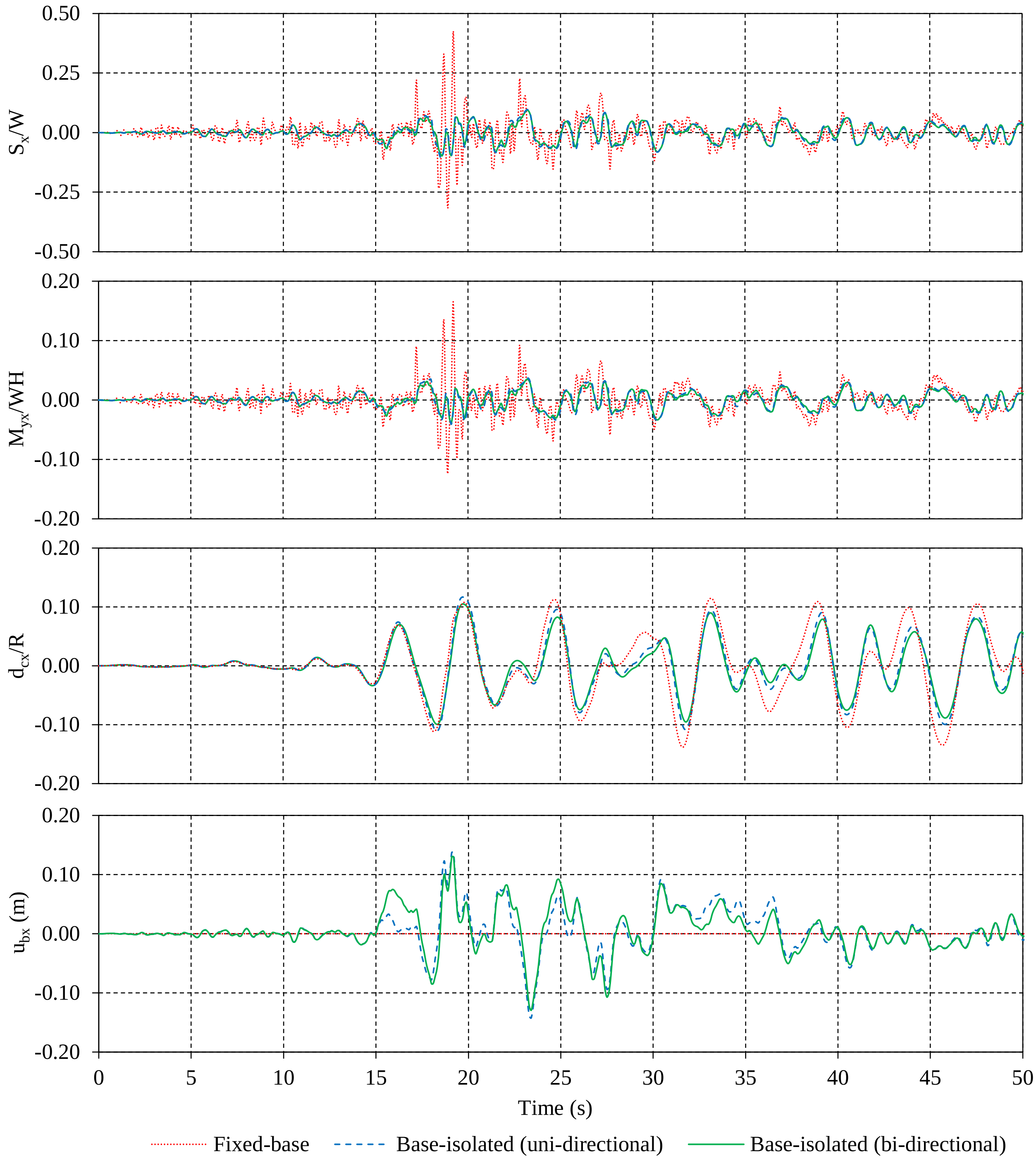

Fig. 6 – Seismic responses in time for the fixed-base and base-isolated systems (H/R = 1.0, e/R = 0.02; ζ_b = 0.25, T_b = 4 s and F_y/W = 0.05) due to Pisco 2007 earthquake (scaled ground motion)

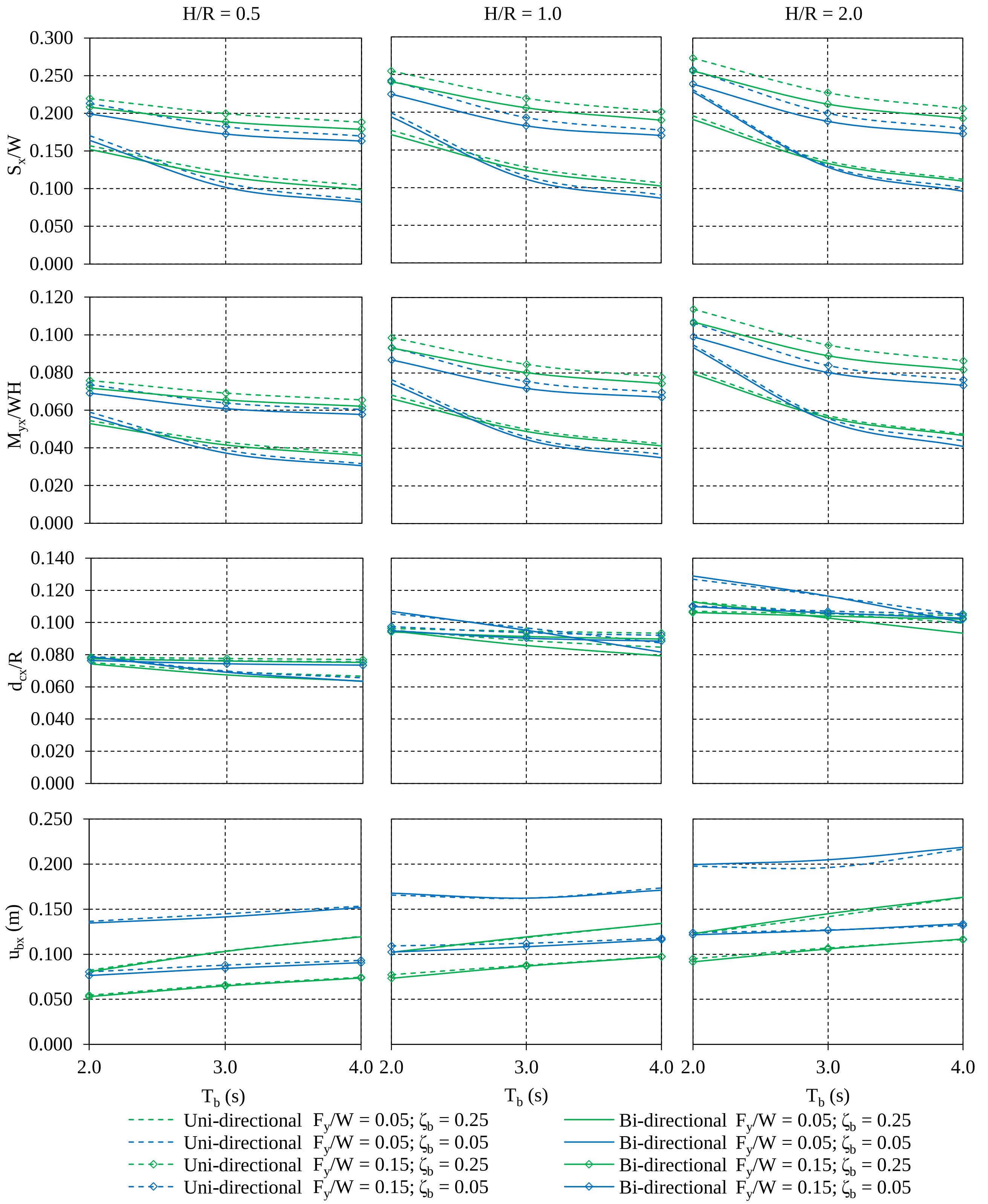

Fig. 7 – Effects of parameters F_y/W, T_b, and ζ_b on normalized design seismic responses of base-isolated systems with e/R=0.02; H/R = 0.5, H/R = 1.0, and H/R = 2.0

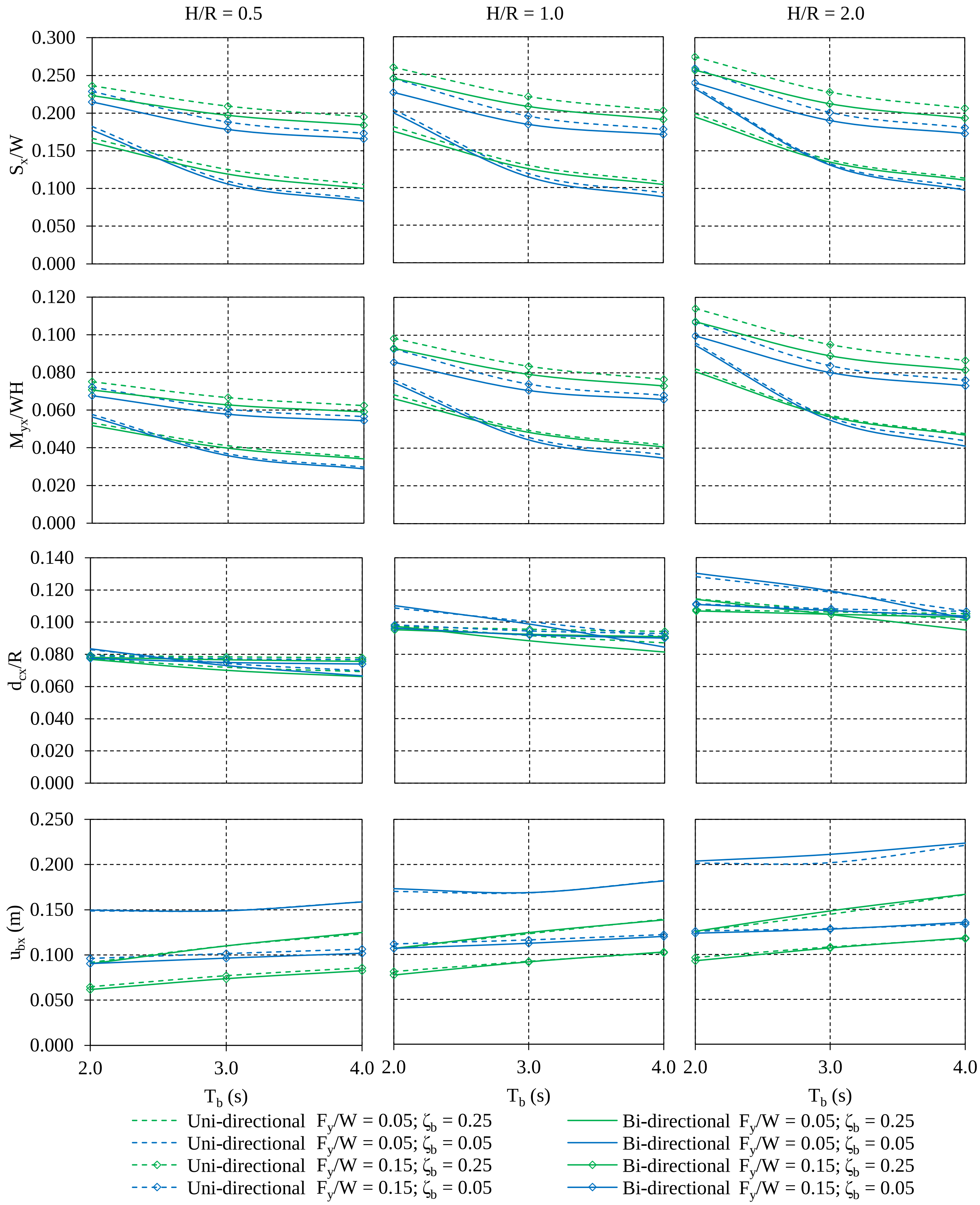

Fig. 8 – Effects of parameters F_y/W, T_b, and ζ_b on normalized design seismic responses of base-isolated systems with e/R = 0.04; H/R = 0.5, H/R = 1.0, and H/R = 2.0

4. Conclusions

The following research conclusions are valid for the group of parametric cases defined in Tables 2 and 3, 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 an insignificant effect on the order of 9% on seismic responses.
2. The reduction in base shear when compared to fixed-base systems is 14% to 74% for H/R = 0.5; 47% to 83% for H/R = 1.0; and 73% to 91% for H/R = 2.0.
3. The reduction in overturning moment of the walls when compared to fixed-base systems is 16% to 71% for H/R = 0.5; 50% to 83% for H/R = 1.0; and 75% to 91% for H/R = 2.0.
4. The variation in vertical sloshing displacement when compared to fixed-base systems is −21% to 7% for H/R = 0.5; −18% to 20% for H/R = 1.0; and −7% to 35% for H/R = 2.0.
5. The parameter F_y/W has a higher effect than the parameter T_b; and the parameter T_b has a higher effect than the parameter ζ_b, in the reduction of the base shear and overturning moment of the walls. When lowering F_y/W, increasing T_b, and reducing ζ_b, the isolation system becomes more effective in reducing the base shear and the overturning moment of the walls.
6. The design parameters associated to the maximum reduction of base shear are e/R = 0.04, F_y/W = 0.05, T_b = 4 s and ζ_b = 0.05 for H/R = 0.5. These values achieve a reduction in base shear on the order of 74% for H/R = 0.5.
7. The design parameters associated to the maximum reduction of base shear are e/R = 0.02, F_y/W = 0.05, T_b = 4 s and ζ_b = 0.05 for H/R = 1.0 and H/R = 2.0. These values achieve a reduction in base shear on the order of 83% for H/R = 1.0; and 91% for H/R = 2.0.

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